N INTRODUCTION TO PRACTICAL PHYSICS

D. RINTOUL

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AN INTRODUCTION

TO

PRACTICAL PHYSICS

Physics Gen.

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PRACTICAL PHYSICS

FOR USE IN SCHOOLS

BY

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PREFACE

THIS introduction to Practical Physics is published in the hope that it will be found of use by those who are engaged in teaching the subject to boys of about thirteen or fourteen years of age and upwards. It is based on the Laboratory notes which have been in use at Clifton for some years past, and the proof-sheets having been used in the Laboratory for some months, have thus received the criticism of those for whom the book has been primarily written. This fact enables the author to feel confident that the book will present no difficulty to the average boy of the age which has been mentioned, and that all the experiments described are capable of being performed with the most simple and inexpensive apparatus.

A word of explanation may be given as to the principles on which the book is based. A somewhat extended experience of teaching experimental Physics to large classes in a Public School has convinced the author that it is possible for a boy to "work through" a course of Practical Physics in such a way as to lose many of the advantages of this kind of study. If the explanations given in the text-book are too detailed, and if the conclusions to be drawn from each experiment are explicitly stated, a boy may perform the experiments, and write out a fairly clear account of them; yet this account may be nothing but a transcript or

a paraphrase of the text-book. All incentive to independent thought is here withdrawn, except in the case of boys who are greatly interested in the subject; and instead of a spirit of scientific curiosity being developed it is rather discouraged, since it is to the apparent interest of the pupil to hurry over the ground as fast as possible. The laboratory work becomes, like many other school lessons, a matter of learning certain facts, no doubt of considerable importance, without the mental training being different in kind from that conveyed in other branches of school work.

In the course here described, an attempt is made to induce the pupil to think for himself, and to treat each experiment as a problem which he himself has to solve; while the solution is rendered possible by suggestions given in the form of questions which he has to answer. Thus, after being told what he has to do, the pupil is asked what the result of his experiment has been—what consequences he has seen to result from certain operations. Instead of the conclusions to be drawn from the experiment, or the appropriate chain of reasoning, being explicitly stated, they are indicated by a series of questions which the pupil has to answer. If he cannot answer any of the questions he should go to the teacher, who can generally induce him to answer the question himself by one or two other questions judiciously put, or, what is easier but less instructive, can give the answer at once. So far as the author's own experience has gone, he is a very dull boy indeed who cannot work through nearly the whole course with the very minimum of help from the teacher. It may here be noted, that the pupil should be taught to write out his notes in such a way that reference to the book on the part of the teacher is unnecessary. Thus, instead of merely writing the answers to the questions in the text, the questions themselves should either be written down, each followed immediately by its

answer, or else the answers should be in such a form that there can be no doubt what the questions were. It is hardly necessary to say that the latter is much the better method.

There are many advantages which ought to be derived from some such method as this of treating the subject. The student is compelled at nearly every step to *think* for himself; his interest in his work is more easily sustained; he learns how to find out things for himself, that is, he is taught to learn from his own observations and not from books or teachers; and the knowledge which he has thus obtained is so much the more easily remembered for the effort with which it has been acquired.

If the teacher is wise, he will encourage all independence of thought. Above all things, the student must believe that what he honestly sees for himself is true and right, and that no statement of text-book or teacher should cause him to say that he has seen anything which he has not seen, or otherwise than he has seen it.

The course has been arranged in the order in which the subjects are usually taken by boys on the modern side at Clifton; but it is possible to take them in any order which the teacher may consider most suitable. For some reasons it may be desirable to take Part III. before Part II., but this must depend, to some extent, on the arrangements made for the teaching of Physics in each particular school. It will be noticed that certain experiments are marked with an asterisk. These are experiments which (mainly on account of their difficulty) may with advantage be omitted by younger boys on taking the subject for the first time.

The introductory chapter on "General Instructions" is intended primarily for the teacher. The matter contained in it is best given to the pupils in the form of lectures; and what is here written is designed to take the place of

notes of such lectures, so that the student may refer to it in the course of his work.

It has not been considered necessary to append a list of apparatus and prices, since price-lists of apparatus suitable for such a course as this are now issued by several well-known firms of instrument-makers. The author will be pleased to give any information on this subject to teachers who will communicate with him. He will also be very grateful for any suggestions which may tend to make the book more generally useful.

In conclusion, the author desires to express his thanks to the friends who have helped him in various ways to make this book less imperfect than it otherwise would have been. Especial thanks are due to Mr. H. Clissold, Mr. G. W. Palmer, and Mr. A. T. Simmons for reading the proofs and making valuable suggestions. In addition, he would desire to express his indebtedness to his predecessor at Clifton, Professor A. M. Worthington, F.R.S., whose *First Course of Physical Laboratory Practice* was the pioneer work in this field, and to whom, therefore, all teachers of the subject owe a debt of gratitude.

D. R.

CLIFTON COLLEGE,
September 1898.

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PART III

Dynamics

GENERAL INSTRUCTIONS

Importance of writing careful notes of experimental work.—It is of the greatest importance on all grounds that the student should early cultivate the habit of writing the pencil notes which he writes in his laboratory note-book (*not* on loose sheets) as carefully and clearly as possible. These notes should be as short as is consistent with clearness, and they should be written in such a way that any person of ordinary intelligence can understand from them exactly what the writer has done.

It is one of the most important educational results which can be obtained from such a course as this, that the student should learn to write clearly and briefly an intelligible account of his work, and, if this is not continually insisted upon, much of the value of this form of education is lost. The words used should be as short and simple as possible. On the other hand, no striving after conciseness must be allowed to interfere with absolute clearness. The ideal which the student should set before himself is this, that any person of ordinary intelligence on reading his description should understand it so clearly as to be able to repeat the experiment for himself

if he so desire it. In fact, he should strive to make his meaning clear even to people of less than ordinary intelligence, remembering the warning given by a distinguished general to his staff officers with reference to the writing of orders: "Remember that any order has to be read by at least *one* idiot."

Another point, which must be kept in remembrance, is that every measurement taken should be *written down when it is made.* Sometimes a whole experiment has to be repeated because some one measurement was not written down, or written down correctly. If everything is thus written down, it is possible for the teacher or the student himself to find out where a mistake has been made, if not, the whole has to be repeated, and a great deal of valuable time wasted. The same remark applies in a minor degree to the arithmetical working. It is convenient to write the description of the experiment on one side of a page, leaving the other side free for the arithmetical processes.

Advantage of making large measurements.—The accuracy of measurement is greatly increased if the thing to be measured is large, and, where any choice is possible, it is always a great advantage to take as large a specimen of the substance, any of whose properties are to be measured, as is possible consistently with convenience. In many cases it is possible to obtain very accurate results by quite simple means if this consideration is attended to. This can be best shown by one or two examples.

In measuring the radius of a circle, although it is theoretically as correct to measure the distance from centre to circumference directly, yet in practice greater accuracy may be expected if we measure the diameter and halve the result. For the error made in measuring the radius is likely to be just as great as that made in measuring the diameter; hence, in the result which we obtain by the

second method, the error is halved since the whole measurement is halved.

Again, if we wish to find the number of square centimetres in 1 gramme of cardboard, as in Experiment 8, the accuracy of our result is much greater if the rectangle which we cut out is a large than if it is a small one. If the rectangle has an area of 100 sq. cm. the error in our measurement may be no smaller than that which we should make in the case of a rectangle of 10 sq. cm., but the proportion which this error bears to the whole thing measured is much smaller in the former than in the latter case. Examples of this will be found in Experiments 3 and 4, and generally throughout the book.

In applying this principle, however, it must be borne in mind that it is applicable only in cases where an increase in the size of the quantity to be measured does not increase the difficulty of measurement.

Estimation of the degree of accuracy of a result.—In connection with this it is to be noted that the accuracy of a result is to be measured not by the *difference* between the correct result and that which is obtained, but by the *ratio* (best expressed as a percentage) which this difference bears to the whole. For example, in Experiment 7, where we obtain three different results for the area of a triangle, the average of the three results may be taken as the correct value of the area. The difference between any one of the three results obtained and the average may be great or small. What is of importance is that this difference should not be a large fraction of the average. The most convenient way of expressing the importance of the error is to find what percentage[1] it is of the quantity measured. For

[1] To express a ratio as a percentage we multiply it by 100. For example, $\frac{1}{2}$ is 50 per cent, $\frac{1}{4}=25$ per cent, $\frac{6.3}{87}$ is $\frac{6.3}{87} \times 100 = \frac{630}{87} = 7.2$ per cent, etc.

example, in an experiment such as Experiment 7 the following were the results obtained :—

With AB as base, area	=	72.64 sq. cm.
With BC as base, area . . .	=	71.98 ,,
With CA as base, area . . .	=	72.14 ,,
	3	216.76
∴ Average of the three . . .	=	72.25 sq. cm.

Here the difference between the first result and the average is $72.64 - 72.25 = 0.39$ sq. cm.

$$\text{The percentage error} = \frac{\cdot 39}{72.25} \times 100 = \frac{39}{72.25} = .5 \text{ nearly}$$

As a rule, in the experiments in Part I. an accuracy of 1 per cent should be obtained.

Importance of large errors.—There is a great tendency for beginners, in striving after extreme accuracy, to be careless in noting the large numbers in their result. Thus, in measuring the length of a line, an error may be made in the number of centimetres through attention being concentrated on the decimals of a millimetre. To obviate this danger it is very convenient in making a measurement of any kind to write down first the approximate value and then to write the accurate value after it.

For example, in weighing, the number of grammes should be written down accurately before the final adjustment is made ; in measuring a length, the number of centimetres should first be written down approximately before writing down the final result.

A great deal of time and trouble will also be saved if the student makes a rough mental estimate as to the probable value of the measurement he is about to make, or a rapid though rough mental calculation of the result of any arithmetical process. In this way the large errors produced

by a mistake in placing the decimal point, or other similar mistakes, may very often be detected.

Suppose, for example, that in measuring a cylinder we find its height to be 4.76 cm., and its diameter 3.24 cm. Before working out accurately the result of the calculation

$$\frac{22}{7} \times 1.62 \times 1.62 \times 4.76$$

it is well to go rapidly through the following calculation, $3 \times 2 \times 2 \times 5 = 60$, so that the answer will be less than 60. As a matter of fact, it is 39.261; so that if in working out, the result came to 3.9261 or 392.61, the student would at once see that a mistake had been made. The example just given is one of the least favourable that could be chosen; as a rule the rough estimate comes much nearer to the correct result than this.

Contracted method of multiplication.—Though not essential, it is a matter of great convenience that multiplications should be carried out in such a way that approximate results can be easily obtained. Thus, if we have to multiply together 48.714 and 3.142 we may do it in either of the following ways :—

$$\begin{array}{r}
48.714 \\
3.142 \\
\hline
97428 \\
194856 \\
48714 \\
146142 \\
\hline
153.059388 \\
\hline
\end{array}
\qquad\qquad
\begin{array}{l}
48.714 \\
3.142 \\
\hline
146.142 \\
4.8714 \\
1.94856 \\
97428 \\
\hline
153.059388 \\
\hline
\end{array}$$

Both methods give the same result, but if we only wish to have the result correct to a certain number of significant figures, the *second method* allows us to obtain the result much more quickly. In addition to this, the most important

figure in the multiplier is used first instead of last as in the first method. (For further details see Lock's *Arithmetic.*)

Meaning of "Proportional" and "Inversely Proportional"

One quantity is said to be **proportional to** *another if the two quantities are so related that the result of* **dividing** *one by the other is always the same however much the quantities themselves may vary.*

The result of dividing one quantity by another is called the **ratio** *of the first to the second.*

Examples.—1. The price paid for a commodity is generally proportional to the quantity of that commodity bought.

2. The weight of any substance in a given volume is proportional to the volume. Thus if 4 c.c. of turpentine weigh 3.28 gm., 5 c.c. weigh 4.35 gm., 12 c.c. weigh 10.44 gm. and so on, the result of dividing weight by volume being always the same however much the weight and volume may vary.

Test of proportionality.—Thus if we wish to test whether one thing is proportional to another we obtain a number of simultaneous values of the two things, and find the result of dividing one by the other in each case. If all these "ratios" are the same, the quantities are proportional to one another.

Inverse Proportion

One quantity is said to be **inversely proportional** *to another when they are so related that any increase in one is accompanied by a decrease in the other, in such a way that the result of* **multiplying** *the two quantities together is always the same however much the quantities themselves may vary.*

Examples.—The time taken to do a certain piece of work is inversely proportional to the number of men working. If 4 men do a piece of work in 6 days, 3 men will do it in 8 days, 2 men in 12 days, 12 men in 2 days, etc., the result of multiplying the number of men and number of days being always the same.

Test of inverse proportion.—Thus, to test whether one quantity is inversely proportional to another, we obtain any number of pairs of simultaneous values of the two quantities. If the result of multiplying these quantities in pairs is in each case the same, the quantities are inversely proportional to one another.

Note.—When two quantities are so related that when one increases the other diminishes in such a way that the *sum* of the two is always the same, the two quantities are said to be *complementary* to each other.

Curve drawing.—The results of an experiment can often be shown very clearly by means of "squared" paper, sometimes called "logarithm" paper, *i.e.* paper divided up by two sets of parallel lines into small squares.

This method is particularly valuable in showing the result of experiments made with the object of finding the way in which one quantity varies, when some other quantity on which the first depends is varied. For example, in an experiment to find how the volume of a given quantity of air varies when the pressure exerted on it is varied, or to find how the volume of the same quantity of air changes as the temperature is varied, or to find how the bending produced in a beam of given length by a given weight depends on the thickness of the beam, or any other experiment of a similar kind, this method is of great use.

Two lines called the "axes" are drawn at right angles to each other, such as OX and OY in Fig. 1. OX horizontally to the right, OY vertically upwards. Suppose that the

experiment is one to find the relation between the volume of a body and its temperature, and that the measurements which we have made are as shown in the table :—

Temperature .	0	10	20	30	40	50
Volume . . .	98.0	106.0	115.0	128.0	144.8	168.0

Corresponding values of temperature and volume being placed one below the other.

Mark every tenth division along OX, *i.e.* every thick

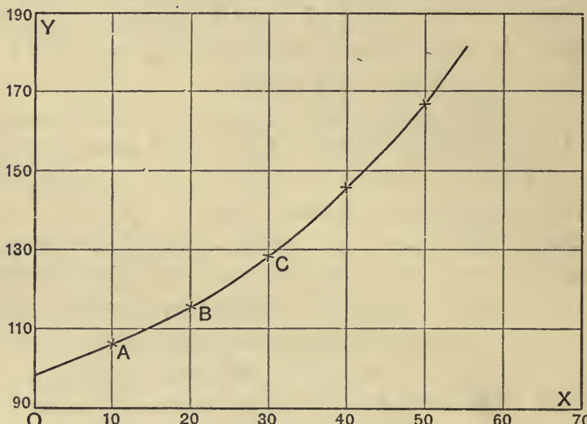

Fig. 1.

line, 10, 20, 30, etc., and on OY mark the point O as 90, the first thick line 110, the second 130, the third 150, etc. Thus every division on the horizontal line represents 1° C., and every division on the vertical line represents 2 units of volume. (Distances measured along the horizontal line are called *abscissæ*, distances measured vertically upwards are called *ordinates*.) Mark on the paper a series of points by means of crosses made with a sharp-pointed pencil, in such a way that the lines drawn through each point parallel to the axes intersect the axes at distances from O represent-

ing the temperature and volume of the body respectively. Thus A is got by making a cross on the vertical line through "10" on the axis of abscissæ, and on the horizontal line through "106" on the axis of ordinates. Similarly B is obtained by taking a horizontal distance 20, and a vertical height 115.0, and so on.

Having in this way marked on the paper a cross for each observation made, a smooth line should be drawn freehand so as to pass through all these crosses, or, if that is impossible, so as to have all the crosses as near to it as possible, *i.e.* so that there should be as many on one side of the line as there are on the other. In this way it is often possible to detect an error in a measurement, because, if nearly all the crosses be well on the line, while one or two are at a considerable distance from it, it is probable that an error of observation was made in noting the measurements on which the positions of these crosses depend.

It is convenient always to draw your curves in such a way that the numbers increase from left to right, and from below upwards. It is also convenient to represent the quantity which you cause to vary by measurements along the horizontal axis, *i.e.* by abscissæ, while the quantity which changes as a result of that variation is represented by ordinates. In some cases this may not be a very obvious distinction, but in these cases it will not matter which is chosen for ordinates and which for abscissæ; but in the majority of experiments there is no difficulty. Thus, in the example given above, we wish to find the change in volume produced by change in temperature, and thus we make the former the ordinate and the latter the abscissa. Again, if the experiment is to find how the flexure of a beam depends on the bending weight, we make the abscissæ represent bending weight and the ordinates flexure.

Another point that is worth noting is that the scale, which is taken to represent any quantity, should be neither too large nor too small. It should be such that the accuracy of the actual measurement should be of the same order of magnitude as the accuracy with which it is represented. For example, if we are using an ordinary thermometer on which we can only estimate tenths of a degree, it would be misleading to represent 1° C. by a space larger than say 1 cm. As a rule, it will be found convenient in most cases to choose the smallest division on your paper to represent the last figure in your measurement, of which you can be absolutely certain that it is correct.

PART I

MENSURATION AND HYDROSTATICS

CHAPTER I

MENSURATION

Measurement of Length

The simplest measurement which we can make is that of the distance between two points on a sheet of paper, *i.e.* the measurement of length. The unit of length on the metric system, which is that in use in all civilised countries except the British Empire and the United States, and which has been adopted by men of science in all countries, is the Metre. This standard of measurement was selected because it was supposed to be one ten-millionth part of the distance from the Pole to the Equator, measured through Paris. This distance was measured as accurately as was possible at the time at which it was done (1791-98), and a bar of platinum was made, and its length carefully adjusted, so that when at a temperature of 0° C. (*i.e.* when surrounded by melting ice) it should be exactly one ten-millionth part of the quadrant of the earth's circumference

as above described.[1] This bar, called the *mètre des Archives*, was taken as the primary standard with which all other standards should be compared, and all metre measures wherever used are copies of this.

Measurements of the earth's quadrant, which have been made later, have shown that the *mètre des Archives* is not accurately one ten-millionth of the quadrant; but as the reasons for its adoption as a standard are independent of its relation to the size of the earth, the length of the standard has not been altered. Thus the metre is defined to be *a length equal to that of a bar of platinum kept in Paris* (*and called the mètre des Archives*), *when at the temperature of melting ice.*

Subdivisions and multiples of the metre.—Just as the yard is divided into the foot and inch, so the metre is divided into smaller portions called the Decimetre, Centimetre, and Millimetre, the prefixes indicating the fraction of a metre. Thus the decimetre (*decem*, ten) is $\frac{1}{10}$ of a metre, the centimetre (*centum*, a hundred) $\frac{1}{100}$ of a metre, and the millimetre (*mille*, a thousand) $\frac{1}{1000}$ of a metre.

Similarly great lengths can be measured in Decametres, Hectometres, and Kilometres, these prefixes being derived from the Greek numerals δέκα, ἑκατόν, and χίλιοι; thus we have:—

1 millimetre (mm.)	$=\frac{1}{1000}$ metre.
1 centimetre (cm.)	$=\frac{1}{100}$ metre.
1 decimetre (dm.)	$=\frac{1}{10}$ metre.
1 metre.	
1 decametre (decam.)	= 10 metres.
1 hectometre (hectom.)	= 100 metres.
1 kilometre (km.)	= 1000 metres.

In Fig. 2 we have a copy of a part of a metre or half-metre scale as used in the laboratory; the long lines with

[1] For further particulars see H. W. Chisholm's *Weighing and Measuring*, Macmillan and Co., 1877.

the numbers show centimetres, and the smallest divisions are millimetres.

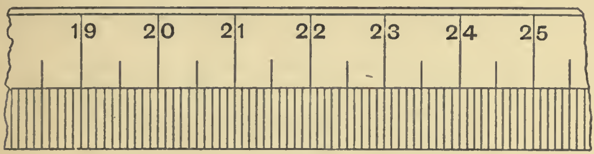

Fig. 2.

Relation between English and metric units of length.—It is convenient for some purposes to know the relation between the metric units and the corresponding English units of length. The following are easily remembered, and are only approximate; if more accurate values are wanted they can be obtained from a book of tables.

1 metre $= 1\frac{1}{11}$ yds.
1 inch $= 2.54$ cm.
1 mile $= 1.6$ km.

Use of the metre scale.—Since all the measurements made in a physical laboratory are comparatively small, they are generally measured in centimetres. Thus if we measure a distance we do not express it as so many decimetres, centimetres, and millimetres, *e.g.* 3 dm., 4 cm., 6 mm., but in centimetres and decimals of a centimetre, thus 34.6 cm.

Also, since the ends of a metre measure become worn by constant use, it is well not to place the end of the measure at the end of the line to be measured. For example, if the distance between two points A and B on a sheet of paper is to be measured, the scale should be placed so that the mark "10" on it coincides with A, and the position of B on the scale is then read off. If this should be 16.8, then the distance AB is 6.8 cm. Again, the scale should be held in such a way that the graduations

come right down to the paper as in Fig. 3, and not as in Fig. 4. In the former case the position of B on the scale

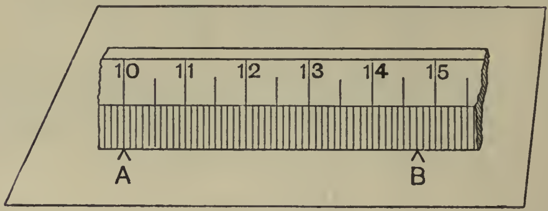

Fig. 3.

is the same wherever the eye may be placed, but in the latter the eye must be held so that the line drawn from it to B may be perpendicular to the scale, otherwise the reading will be either too great or too small, according as the eye is in position F or position G.

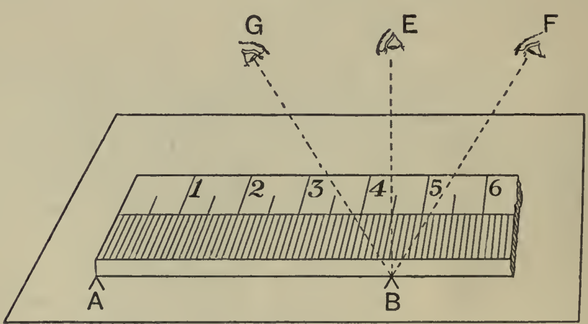

Fig. 4.

[The error introduced by varying the position of the eye, as in Fig. 4, is one which it is sometimes difficult to avoid in physical measurements, and is called *parallax*. Examples of it will be found in reading thermometers, burettes, etc.]

Estimation of tenths of a millimetre.—It will generally

be found in measuring a length that after the scale has been placed with the "10" mark exactly on one end of the length to be measured, the other end lies not exactly on one of the millimetre divisions, but between two of them. In this case the actual position on the scale should be estimated by eye, and with a little practice considerable accuracy in this may be attained.

The way in which it is easiest to make this estimation is to imagine the distance between the two millimetre lines to be divided into 10 equal parts, and judge how many of these parts lie on the left of the point whose position on the scale is to be found. Thus in Fig. 5 the point A would

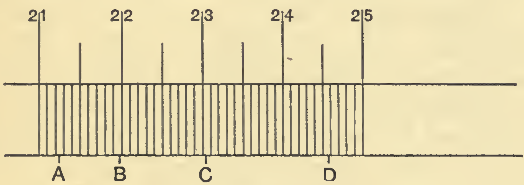

Fig. 5.

have for its reading 21.24 cm., because if the distance between 21.2 and 21.3 were divided into 10 equal parts, 4 of these would be on the left of A. Similarly, we should have for B, C, and D, 21.98, 23.03, and 24.58, respectively.[1]

It should be noted that if a reading is exactly on a line, *e.g.* 24, it should be written 24.00. If we say a length is 24 cms. we mean that it is nearer 24 cms. than 23 or 25, but if we say it is 24.00 cms. we mean it is nearer 24.00 cms. than 23.99 or 24.01 cms.

[1] This can be very quickly learned by a class if the master draws on the blackboard an enlarged picture of part of a scale such as that shown in Fig. 5, and asks each member of the class to state the position on the scale of the point of a rod, such as a pointer, changing the position of the pointer each time.

Measurement of a curved line.—A curved line may be measured by means of a flexible cord, such as a piece of cotton, in the following manner:—Suppose that we have to measure the length of the curve in Fig. 6. Take a piece of cotton of sufficient length, and tie a knot near one end.

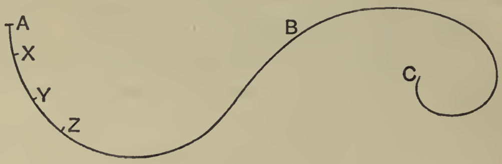

Fig. 6.

Place this knot on the paper at A, and hold it tight with the left hand. With the other hand stretch the cotton along the curve to such a distance AX that the string coincides with the curve. (It is obvious that this distance AX will depend on the curvature—the greater the curvature the shorter the length of cotton which will coincide with the

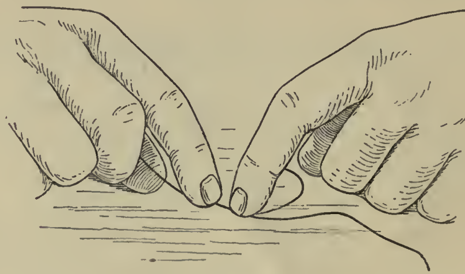

Fig. 7.

curve.) Hold the cotton down on the curve at X with the thumb of the right hand, let go with the left hand, and place the thumb or forefinger of the left hand close to the right at X. Holding the thread at X with the left hand, stretch the cotton another short distance XY as before. In

this way the cotton can be laid along the whole of the curve ABC. When C is reached with the thumb of the right hand, lift the cotton with this hand without allowing the cotton to slip, and lay it straight along the metre measure. Thus the length of the curve can be measured by measuring the length of the cotton which can be made to lie along it.

Measurement of Area

By area we mean extent of *surface*. The unit of area which we use is the area of a square each of whose sides is 1 cm. long. This is called a *square centimetre* and written **sq. cm.** Thus to find the area of any surface, we have to find how many square centimetres it contains.

We need here only consider plane surfaces, or surfaces which can be unwrapped so as to form planes, *e.g.* cone, cylinder.

Area of a Rectangle

The area of a rectangle is found by multiplying together its length and breadth (both measured in cm.).

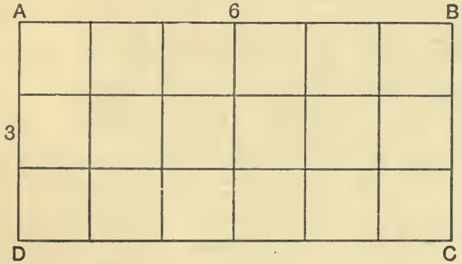

Fig. 8.

Thus, suppose the rectangle ABCD to be 6 cm. long and 3 cm. broad, we can divide AB into 6 parts each 1

cm. long, similarly AD can be divided into 3 parts each 1 cm. long. Through each of these points of division draw straight lines parallel to the sides of the rectangle, so that the area of the rectangle is divided up into squares. Each square is 1 sq. cm., and there are 6 of them in each row, and there are three rows. Hence in this case there are $3 \times 6 = 18$ sq. cm. in the area.

By similar reasoning, whatever may be the number of centimetres in the length and breadth, the number of square centimetres in the area will be got by multiplying the two together. And if there should not be a whole number of centimetres in the length or breadth the same reasoning still holds good.

Area of a Triangle

To find the area of a triangle, multiply any side by the perpendicular drawn from the opposite angle to that side or that side produced and halve the result.

Thus the area of the triangle ABC is $\frac{1}{2}$ BC × AD or $\frac{1}{2}$ AB × CF or $\frac{1}{2}$ AC × BE.

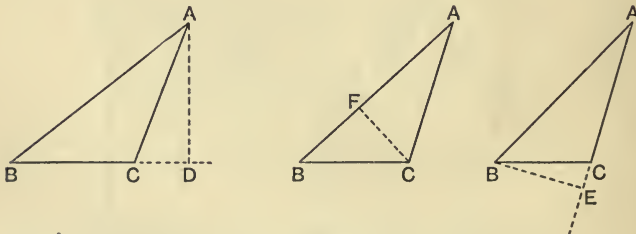

Fig. 9.

For by *Euclid*, i. 41 the area of the triangle ABC is half the area of a rectangle on the same base BC and having the same altitude AD, hence the area of the triangle

is $\frac{1}{2}$ BC × AD. Similarly the other expressions may be proved, each side in turn being taken as base and the perpendicular drawn from the opposite angle to that side or that side produced as altitude.

Area of a Circle

To find the area of a circle, square the radius and multiply by π. (See p. 20.)

This is to be proved experimentally in Experiment 8. (See p. 24.)

It may also be proved as follows, from the result of Experiment 3 :—suppose the circumference of the circle divided up into a large number of very short pieces such as AB, BC, CD, DE, etc., and lines drawn from the centre to

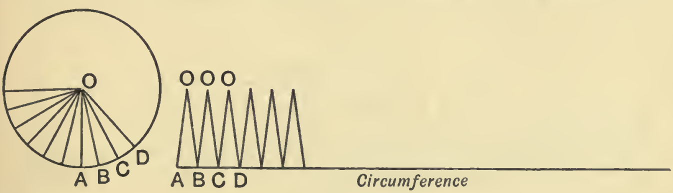

Fig. 10.

ABCD, etc. Then the area of the circle is got by adding together the areas OAB, OBC, OCD, etc. But if AB is very small OAB is practically a triangle whose base is AB, and the perpendicular drawn from the vertex O to the base is = OA or OB. Hence the area of OAB = $\frac{1}{2}$ OA × AB = $\frac{1}{2}r$ × AB where r = radius of circle.

Similarly the area of OBC = $\frac{1}{2}\,r \times$ BC

Similarly the area of OCD = $\frac{1}{2}\,r \times$ CD etc.

Hence the area of the circle = $\frac{1}{2}\,r \times$ AB + $\frac{1}{2}\,r \times$ BC + $\frac{1}{2}\,r \times$ CD + etc.

= $\frac{1}{2}\,r \times$ (AB + BC + CD + . . .)

But AB + BC + CD + etc. = circumference of the circle.

Hence area of circle = $\frac{1}{2}\,r \times$ circumference.

But circumference = diameter × π (see p. 20) = $2r \times \pi$

Hence area of circle = $\frac{1}{2}r \times 2r \times \pi = \pi r^2$

Area of Figure of any Shape

It is only in the case of a few regular figures that the area is connected by any simple relation with the linear dimensions, so that it can be calculated from those dimensions. In the great majority of cases some other method must be used, and the following is one of the most convenient.

Draw the figure, whose area is to be found, on a sheet of cardboard or sheet-metal of uniform thickness, cut out the figure and weigh it. If we know, by a separate experiment, how many square centimetres of the sheet weigh 1 gramme, we can thus find the area of the figure which has been cut out. Details of the method will be found on p. 24.

Examples

1. Find the area of a rectangle whose length is 18.4 cms. and breadth 6.2 cms.

2. A right-angled triangle has its sides containing the right angle 16.2 and 7.3 cms. long. Find its area.

3. Find the area of a circle whose radius is 8.4 cms.

4. Find the area of a circle whose diameter is 20.3 cms.

5. The area of a circle is 468.52 sq. cms., find the square on its radius.

6. A sheet of copper 12.4 cms. long, 8.2 cms. wide, weighs 42.30 gms. Find the area of the sheet which weighs 1 gm.

7. A figure drawn on a sheet of uniform cardboard weighs 8.7 gms., and a rectangular piece of the same card 15.20 cms. long, 8.32 cms. wide, is found to weigh 7.6 gm. What is the area of the figure?

8. A circular piece of cardboard whose diameter is 10.2 cms. is found to weigh 7.5 gms. What will be the area of a circular piece of the same cardboard weighing 10.0 gms.?

[Answers should be worked out to four significant figures.]

Measurement of Volume

By the *volume* of a body we mean the *space which it occupies* or its cubic contents.

The unit of volume which we generally use is that of a cube, each of whose edges is 1 cm. long. This is called a cubic centimetre, and is written **c.c.**

As in the case of areas of surfaces, there are a few regular solids whose volumes can be found by measurement of their linear dimensions and calculation from these measurements, but in the great majority of cases the volume cannot be calculated from the linear dimensions, but must be found by some experimental method such as those described on p. 13.

Right Prisms

A right prism is a solid figure bounded by plane faces, two of which are parallel to each other, and the others perpendicular to these two. Either of the parallel faces is called the *base* of the prism.

To find the volume of a right prism, multiply the area of the base measured in square centimetres by the height measured in centimetres.

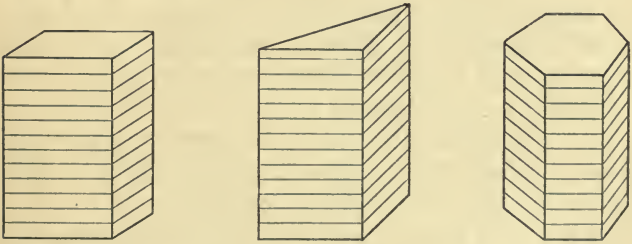

Fig. 11.

The reason for this rule will be seen at once if we

suppose the prism to be cut into a number of slices by planes parallel to the base, each slice being 1 cm. thick. Then in each slice there will be as many cubic centimetres as there are square centimetres in the base. Hence the number of cubic centimetres in the prism will be got by multiplying the number of cubic centimetres in each slice by the number of slices, *i.e.* by multiplying the number of square centimetres in the base by the number of centimetres in the height.

Right Cylinder

A right cylinder is a solid figure bounded by two plane faces parallel to each other, and by a curved face everywhere perpendicular to those faces. Either of the two plane faces is called the *base* of the cylinder.

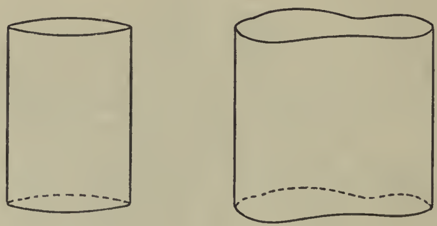

Fig. 12.

When the base of the cylinder is a circle, the cylinder is called a *right circular cylinder.* (In this book, where the word cylinder is used without qualification, right circular cylinder is to be understood.)

For exactly the same reasons as apply to right prisms, the volume of a right cylinder is found by multiplying the area of the base by the height. See Fig. 11.

Thus, since its base is a circle, the rule for finding the volume of a right circular cylinder may be written :—
"*Multiply the square of the radius by π and by the height.*"

Solid of Irregular Shape

As in the case of areas, the number of solids whose volume can be calculated from their linear dimensions is very limited. But since a solid when immersed completely in a liquid displaces a quantity of that liquid whose volume is the same as that of the solid, this gives us a simple means of finding such volumes. We can also in this way find the internal volume (or cubic contents) of a vessel of any shape.

For example, if we wish to find the volume of a vessel of any shape, all we need do is to find what mass of water it contains. Since (p. 16) 1 gm. of pure cold water has a volume of 1 c.c., the volume of the vessel in cubic centimetres is expressed by the same number as the mass of the water it contains measured in grammes.

Similarly, we can find how many grammes of water are displaced by any solid body, and thus also find its volume (see p. 32).

Solids soluble in water.—This method is however not capable of being used in cases where the body whose volume is to be found is acted on in any way by water, *e.g.* it would not be available in the case of rock salt or sugar. In such cases we must find how many grammes of some other liquid which does not act on the solid are displaced by it. But in this case we are not entitled to assume that the number of grammes of liquid displaced is the same as the number of cubic centimetres in its volume. We must, by a separate experiment, find how many cubic centimetres there are in 1 gramme of the liquid which has been used.

The best way to do this is to use a specific gravity flask, which is described on p. 35. We find the volume of the flask by finding the mass of water which it contains, we then find the mass of the given liquid which it contains,

and thus find that so many grammes of the liquid have a volume of so many cubic centimetres, and so find how many cubic centimetres there are in 1 gramme of the liquid.

Importance of using a narrow-necked vessel.—In measuring the quantity of liquid displaced by a solid, we have to adjust the level of the liquid either to a mark on the side of the vessel, or else so as just to fill the vessel. In either case there is a possibility of error in judging the exact position of the surface of the liquid. If the vessel is wide, this error in the position of the surface of the liquid will produce a large error in the result. Thus, in Fig. 13, if the same error AB is made in judging the true position of the surface of the liquid in vessels 1 and 2, the error introduced into the final result will be much larger in the case of No. 1 than of No. 2, because the area of the base

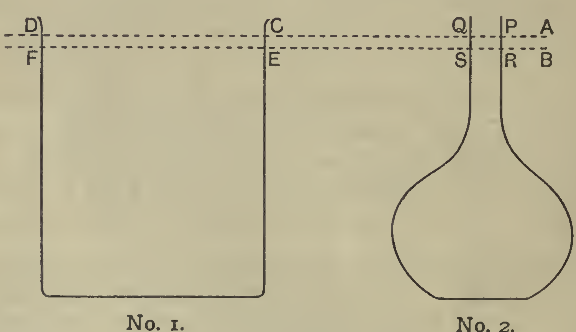

Fig. 13.

of the cylinder CDEF is much greater than that of the cylinder PQRS.

Use of pipette.—The pipette in its simplest form is a glass tube about 20 cm. long and .5 cm. internal diameter, open at both ends. It is used for transferring small

quantities of a liquid from one vessel to another. To take out a small quantity of a liquid from a vessel, the tube is dipped into the liquid, the upper end is then closed with the finger, and the tube withdrawn. By slightly raising the

Fig. 14.

finger the liquid can be allowed to come out of the tube in drops. A more elaborate form of pipette is shown in Fig. 14. Here a larger quantity of liquid can be transferred, and yet small adjustments can be made in the same way.

Measurement of Mass—Weighing

By the *mass* of a body we mean the *quantity of matter in it* as distinguished from the *space* which the body occupies, which, we have seen, is called its volume. In common language the word weight is generally used in this sense; but since the word weight is also used to mean the force with which a body is drawn towards the earth, it is convenient to use different words to mean these two very different things. Unfortunately, no satisfactory word has been coined to express the operation of measuring mass, or what is commonly called "weighing" a body. Probably no serious difficulty is caused, at least in the early stages of such a course as this, by using the word weight when we mean quantity of matter; but it is as well to begin by using the word, which has been by the common consent of physicists adopted for the purpose.

The operation of weighing generally consists in balancing the object to be weighed in one pan of a balance against certain standard pieces of metal called *weights.*

The unit of mass on the metric system is the *gramme* (gm.). It was chosen as being the mass of a cubic centimetre of pure water at a temperature of 4° C., *i.e.* the temperature at which water is densest. Just as the metre, though theoretically deduced from the length of a quadrant of the earth's circumference, is really obtained from the standard metre, so the gramme is actually one-thousandth part of the mass of a certain block of platinum kept in Paris, and called the "*Kilogramme des Archives.*"

The weights used in the laboratory are in boxes or blocks of wood, the fractions of a gramme being under a glass cover. The weights are arranged according to a definite plan, the most common being as follows:—50, 20, 20, 10, 5, 2, 2, 1, .5, .2, .2, .1, .05, .02, .02, .01. Sometimes, instead of the sequence 5, 2, 2, 1, we find the sequence 5, 2, 1, 1.

Thus by means of these weights anything can be weighed correctly to .01 gm., provided it is less than 100 gm. It is well to have a set of larger weights in iron by which we can weigh heavier objects.

It should be noticed that each weight has a definite place in the box, and the student should learn as early as possible to count the weights by counting the *empty spaces in his box*, as well as by counting the actual weights in the scale pan.

Points to be observed in weighing.—The following remarks should be carefully read and thoroughly understood:—

1. The weights must not be touched by the fingers; there are pincers provided for the purpose of lifting them. This applies to all the weights in the box—not only to the fractions.

2. They must be replaced in the box as soon as they are taken off the pan of the balance. *On no account must*

a weight be placed anywhere except on the balance pan, or in its place in the box or block.

3. Before an object is weighed the balance should, if necessary, be adjusted by means of shot, sand, or paper, until the pointer attached to the beam is vertical or swings equally on each side of the vertical.

4. The object to be weighed is then placed in the left-hand pan, and weights placed in the right-hand pan, until the pointer is again vertical or swinging equally on each side of the vertical.

5. The weights are then counted by noting the empty spaces in the box, and again as they are being transferred from the pan to the box, in order to check the result. In doing this the largest weights should be counted first, those belonging to each place of digits being taken together. Thus, if the weights are 50, 20, 10, 5, 1, .2, .2, .05, .02, .01, the "tens" should be counted first and written down —80; then the units—6; then the decigrammes or first place of decimals—.4; then the second place—.08; and the result will then be 86.48 gm.

6. If the result is a whole number of grammes it should be written with a decimal point and two ciphers thus: 24.00 gm. This shows that the result claims to be accurate to the second place of decimals, *i.e.* to a centigramme.

Counterpoising.—Sometimes it is convenient to *counterpoise* an object in the balance instead of *weighing* it, *i.e.* to place it in one pan and to place in the other pan not weights but objects of any kind, such as blocks of iron or lead or shot, sand, paper, etc. The final adjustment can be made very accurately by using paper. For this purpose it is convenient to keep in the box containing the balance a small wooden box (*e.g.* a pill box) containing lead shot.

CHAPTER II

EXPERIMENTS ON MENSURATION

Experiment I

Measure and record the distances AB, BC, CD, DA, AC, and BD, estimating to tenth of a millimetre.

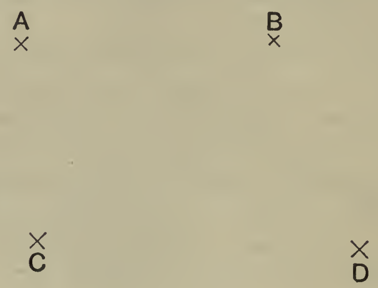

Fig. 15.

The measurements should not be in centimetres and millimetres but in centimetres and decimals, and should be written down in the following form :—

Length of AB = 4.67 cm.
Length of BC = 7.60 cm. etc.

EXPERIMENT 2

Measure the diameter of a penny, a halfpenny, and one of the metal cylinders in your cupboard, and record the results as in last experiment.

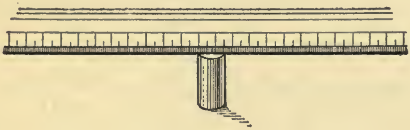

Fig. 16.

Lay the half-metre measure so as to measure each object at its widest part.

There is a number on the cylinder—note it, as you will require it in several other experiments.

EXPERIMENT 3

To find the ratio of the circumference to the diameter of a circle.

[By the ratio of one thing to another is meant the *number of times* that the second is contained in the first, *i.e.* the result of dividing the first by the second. For example, the ratio of a yard to a foot is 3, the ratio of an inch to a foot $= \frac{1}{12}$ or .083, the ratio of x to $y = \frac{x}{y}$.] (See also p. xvi.)

Draw in your note-book three circles of different sizes, but all of them fairly large, for the reason mentioned on p. xii. Measure by means of cotton (see p. 6) the circumference, and by direct measurement the diameter of each circle, and record the results. Then find, correct to three places of decimals, the ratio of circumference to diameter in each case.

Write out your record according to the following model :—

Circle No. 1. Circumference = cm.
Diameter = cm.
$\therefore \quad \frac{\text{Circumference}}{\text{Diameter}} =$

Circle No. 2. Circumference = cm.
Diameter = cm.
$\therefore \quad \frac{\text{Circumference}}{\text{Diameter}} =$

Circle No. 3. Circumference = cm.
Diameter = cm.
$\therefore \quad \frac{\text{Circumference}}{\text{Diameter}} =$

Ratio in the case of No. 1 =
Ratio in the case of No. 2 =
Ratio in the case of No. 3 =

3|________

Average value of the ratio =

Meaning of the symbol π.—It is found that the ratio $\frac{\text{circumference}}{\text{diameter}}$ is the same whatever be the size of the circle, and as the value of the ratio is 3.1415926 . . . it is for convenience sake denoted by the Greek letter π. Thus π is a symbol standing in place of the expression "the ratio of the circumference of a circle to its diameter," or instead of the number 3.1415926 . . .

For ordinary purposes the value of π may be taken as $3\frac{1}{7}$ or $\frac{22}{7}$.

From what you have learned above, write down a rule by which to find the circumference of a circle when you know its diameter.

Also explain how to calculate the diameter of a circle when you know its circumference.

Experiment 4

Indirect measurement of diameter of a cylinder.

Take one of the metal cylinders in your cupboard, the one used in Experiment 2, and make a mark with your pencil on the circular edge. Make a corresponding pencil mark on your paper and roll the cylinder along (taking care that it does not slip), till the mark on it again touches the paper. Mark this point and measure the distance between the two marks on your paper, and record the result, which will be the circumference of the cylinder.

Knowing the circumference, calculate the diameter and compare the result with the result of measuring the diameter directly in Experiment 2.

Which of these results do you consider the more accurate, and why?

Repeat the experiment by rolling the cylinder round three times instead of once, thence find the circumference and diameter of the cylinder.

As a result of your experiment, state how you would proceed to find the diameter of your cylinder with the apparatus at your disposal, if great accuracy were required.

Write your results in the following form:—

Distance between marks on paper when cylinder is rolled round once . . .	=	cm.
∴ diameter of cylinder . . .	=	cm.
Result of Experiment 2, diameter . .	=	cm.
Difference	=	cm.
Distance between marks on paper when cylinder is rolled round three times . .	=	cm.
∴ circumference of cylinder . .	=	cm.
∴ diameter of cylinder . . .	=	cm.

Experiment 5

To measure the diameter of a sphere.

It is impossible to measure the diameter of a sphere directly, and it is difficult to roll it accurately along a straight line. The following method, when carefully carried out, is found to give good results.

Choose two wooden blocks with sharp edges and of a thickness greater than the radius of the sphere, and test them to see whether their angles are right angles. This is done by placing them together with their edges in the same straight line, *e.g.* along your metre or half-metre measure as in the diagram. If their angles are right

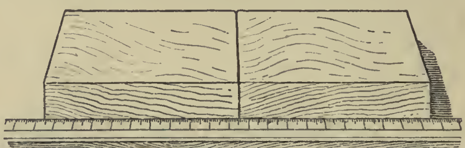

Fig. 17.

angles, the adjacent sides of the blocks will be in contact with each other along the whole of their length.

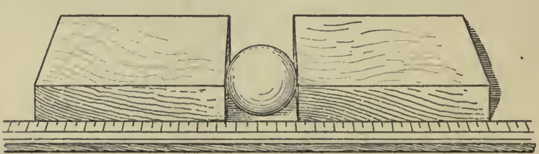

Fig. 18.

Then separate the blocks and place the sphere between them, keeping the sides which were previously in contact with the straight edge still in contact with it, as in Fig. 18. Note where the prolongations of the faces which touch the sphere cut the scale, and thus find the diameter.

Experiment 6

Weigh the cylinder which you measured in Experiments 2 and 4.

Note for the teacher.—The mass of each cylinder should be accurately known and noted in a book kept for the purpose. The result of weighing ought to be correct to within .05 gm. A higher degree of accuracy than this is hardly to be expected with the balances used for this class of work.

Experiment 7

Measurement and calculation of area of a triangle.

Draw on your note-book a triangle with sides 12 cm. 8 cm. and 7.5 cm. long (*Euclid*, i. 22), and find its area by taking each side in turn as base. (See p. 8.)

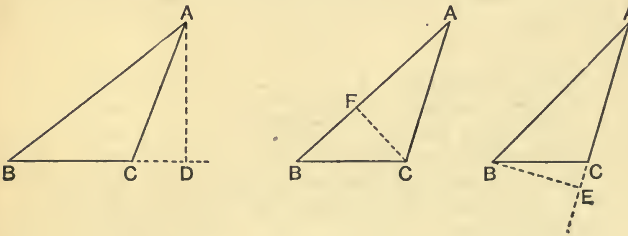

Fig. 19.

Write your results thus :—

BC = cm.
AD = cm.
$\therefore$ Area of triangle $= \frac{1}{2}$ BC × AD = sq. cm. etc.
D

Experiment 8

To find by cutting out and weighing, the area of a circle, and hence to verify the rule given on p. 9 for finding the area of a circle. (See p. 10.)

Take a piece of cardboard and carefully draw upon it an exact rectangle as large as you can get to go into the sheet. (The simplest way to test whether the figure is rectangular or not is to measure the sides and diagonals. If the opposite sides are equal to each other and the diagonals equal to each other then the figure is a rectangle.) Draw inside this rectangle as large a circle as possible.

By means of a knife or pair of scissors cut out the rectangle and weigh it.

Measure and record length and breadth of rectangle, and thus calculate its area.

Then cut out the circle and weigh it.

The following is a model of how the results should be written down :—

Length of rectangle	=	cm.
Breadth of rectangle	=	cm.
∴ area of rectangle	=	sq. cm.
Mass of rectangle	=	gm.
Since gm. of card have an area of .		sq. cm.
∴ 1 gm. of card has an area of .		sq. cm.
Mass of circle	=	gm.
Hence area of circle	=	sq. cm.
Radius of circle (r)	=	cm.
∴ r^2	=	sq. cm.
∴ πr^2	=	sq. cm.
Thus area by cutting out and weighing .	=	sq. cm.
And area by rule	=	sq. cm.
Difference	=	sq. cm.

* EXPERIMENT 9

Using exactly the same method as in last experiment, prove that the area of an ellipse is π times the product of its semi-axes.

An ellipse is a plane figure, such that the sum of the two distances of any point on it from two fixed points called the foci is always the same wherever that point may be. Thus in the diagram:

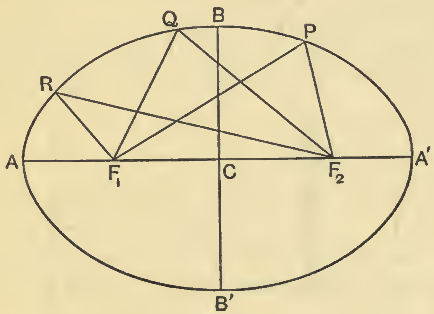

Fig. 20.

$$
\begin{aligned}
&RF_1 + RF_2 \\
&= QF_1 + QF_2 \\
&= PF_1 + PF_2, \text{ etc.}
\end{aligned}
$$

The line AA′ passing through the foci F_1 and F_2 is called the major axis. BB′ bisecting AA′ at right angles is called the minor axis. C is the centre. Thus the semi-axes are AC and BC.

It can be drawn very easily on a piece of cardboard by fixing two pins in the card at two points, such as F_1, F_2, and then making a loop of a convenient size with a piece of cotton, as in Fig. 21. Then place a sharp-

pointed pencil in the loop so as to stretch the string tightly, as in Fig. 22, and move the pencil round the pins, still

Fig. 21.

keeping the cotton tight. The point of the pencil will trace out an ellipse.

The pins should be fixed firmly by pressing them through the card into the table below. This is done most

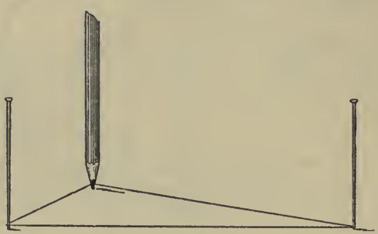

Fig. 22.

effectually by holding the pin within a centimetre of its point with your pliers, and pressing it into the table. If you try to hammer it in, or catch it near the head and press it in, it is likely to bend.

Write out your results according to the form on p. 24, only substituting the word ellipse for circle wherever it occurs, and instead of the 9th, 10th, and 11th lines writing as follows :—

$\frac{1}{2}$ major axis	=	cm.
$\frac{1}{2}$ minor axis	=	cm.
∴ product of semi-axes	=	sq. cm.
∴ $\pi \times$ product of semi-axis . . .	=	sq. cm.

* **Developable surfaces.** — Some curved surfaces are what is called *developable*, that is, they are of such a shape that although curved, a plane sheet of paper can be wrapped round them so as to fit them exactly.

For example, the curved surface of a cylinder and that of a cone can be covered in this way by a flat piece of paper. In the case of a cylinder the surface when unwrapped is a rectangle, while in the second case it is a sector of a circle.

Without trying any experiment—answer the following questions :—

1. A cylinder has a radius of 6 cm. and length 10 cm., what is the length and breadth of the rectangle into which its curved surface can be unrolled? What then is the area of the curved surface of the cylinder?

2. A cone is 8 cm. high, and has a radius of 6 cm. at the base, and the length of its sloping sides is 10 cm. What is the radius of the circular sector into which its curved surface can be unwrapped?

3. What is the length of the arc of this sector?

4. What fraction of the complete circle does this sector occupy?

5. What is the area of this complete circle?

6. What is the area of the sector, and therefore of the curved surface of the cone?

7. Could the surface of a sphere be found in this way?

Experiment 10

Volume of rectangular block.

Find the volume of a rectangular block of wood by measuring its length, breadth, and thickness.

Measure each dimension three times and take the average of the three measurements. Having found the volume of the block, weigh it and record the result. Note also the number of the block.

Experiment 11

Find the volume of the cylinder used in your former experiments. (See p. 12.)

Write your results in the following manner :—

Cylinder No.

Length (1)	=	cm.
Length (2)	=	cm.
Length (3)	=	cm.
Average length	=	cm.
Radius as obtained from Experiment 4 . . .	=	cm.
Area of base $= \pi r^2$	=	sq. cm.
∴ volume = area of base × height . . .	=	c.c.
,, ,,	=	c.c.

The height of the cylinder is measured in three different places in order that any irregularity in its shape may be allowed for. If we measured the diameter directly as in Experiment 2, we should have measured several diameters in case it was not exactly circular. Why is this not necessary when we take the method used in Experiment 4?

Experiment 12

Measure and calculate the volume of a triangular prism.

This should be written down as follows :—

Prism No.

Base of prism is a triangle ; base of this triangle	=	cm.
Altitude of triangle	=	cm.
∴ area of triangular base	=	sq. cm.
Height of prism	=	cm.
Hence volume of prism	=	×

When the volume has been found, weigh the prism carefully and note the result in your book, as it will be required for future reference.

Experiment 13

To test the accuracy of your weights.

If your weights are accurate, the number of grammes of water contained in any vessel whose volume you can find by measurement and calculation, will be the same as the number of cubic centimetres in its volume. For this purpose a cylindrical vessel (such as a calorimeter) should be taken and counterpoised on one pan of the balance. Then fill the vessel with water, accurately adjusting the level of the water by means of a pipette, replace it on the balance pan and weigh.

Then measure the internal diameter of the vessel in at least four places[1] and take the average; similarly find the internal height, and thence calculate the volume as in Experiment 11.

State whether your weights are accurate or not. If they are not accurate, state what is the error in the weights in each gramme, supposing all the weights to be wrong in the same proportion, and being careful to state whether your weights are too heavy or too light.

Experiment 14

Fill the cylindrical vessel used in Experiment 12 with turpentine, after having counterpoised it, and find the mass of turpentine which the vessel contains. What is the volume of the turpentine?

Experiment 14a

Repeat last experiment, using a saturated solution of common salt instead of turpentine.

[1] *Calipers.*—This measurement can be most accurately made by the help of a pair of calipers or dividers. They are adjusted so as just to go inside the vessel, and then the distance between the points is measured on the half-metre measure.

Density

If we make out of a number of different substances such as wood, cork, lead, iron, brass, zinc, a number of blocks all of the same volume, will these blocks have the same mass? If not, which do you suppose, from your own experience, would be the heaviest, and which the lightest? This difference between different substances is expressed by saying that they have different **densities.**

Now in order to compare substances in this way, it is not enough to weigh different specimens of the substances; we must see that the different specimens have the same *volume.* For example, a large piece of wood may be heavier than a small piece of lead. Thus, it is not enough to say that because one thing is heavier than another it is necessarily of denser material — we must either take equal volumes of the two substances or else calculate what would be the mass of the same volume (say 1 c.c.) of each. Thus, if 40 c.c. of a certain kind of wood weigh 30 gm. and 5 c.c. of iron weigh 37 gm., we see that 1 c.c. of the wood weighs $\frac{30}{40}$ or .75 gm., while 1 c.c. of iron weighs $\frac{37}{5}$ or 7.4 gm.

The density of a substance is therefore a thing which belongs to the *substance,* independently of the particular body or thing which the substance is made into. It is in this way quite a different kind of thing from mass, or weight, or volume, or shape, which belongs to a particular *body.* Briefly, density is a property of a *substance,* while mass, volume, shape, etc., are properties of a *body.*

The density of a substance is defined to be **the mass of unit volume of that substance** *or the number of grammes in 1 c.c. of it.* Thus the densities of the wood and iron referred to above are .75 gm. per c.c. and 7.4 gm. per c.c. respectively.

Thus, remember that *when you are asked to find the density of any substance you have to find the mass of* 1 *c.c. of it.*

EXAMPLES

1. A block of brass weighing 864.20 gms. has a volume of 102.8 c.c. Find (correct to 2 places of decimals) the density of brass.

102.8 c.c. of brass weigh 864.20 gms.

$\therefore$ 1 c.c. weighs $\frac{864.20}{102.8}$ gms.

$=8.41$ gms. (nearly).

$\therefore$ density of brass $=8.41$ gms. per c.c.

2. If the density of alcohol be .85 gm. per c.c., what mass of alcohol will be required to fill a bottle whose volume is 683.28 c.c.?

1 c.c. of alcohol weighs .85 gm.

$\therefore$ 683.28 c.c. of alcohol weigh $.85 \times 683.28$ gms.

$=540.788$ gms.

3. If the density of iron be 7.6 gms. per c.c., find the volume of a block of iron weighing 100 gms.

7.6 gms. of iron have a volume of 1 c.c.

$\therefore$ 1 gm. of iron has a volume of $\frac{1}{7.6}$ c.c.

$\therefore$ 100 gms. of iron have a volume of $\frac{100}{7.6}$ c.c.

$=13.16$ c.c. (nearly).

EXPERIMENT 15

Calculate the density of

(*a*) The wood of the block in Experiment 10.

(*b*) The material of which the cylinder used in Experiments 2, 6, and 11 is made.

(*c*) The wood of which the prism of Experiment 12 is made.

(*d*) Water as found from Experiment 13, supposing your weights to be correct. What is the correct value of the density of water?

(*e*) Turpentine
(*f*) Salt solution } of Experiment 14.

Experiment 16

To find the volume of an irregular solid which sinks in water.

If you place the solid in a vessel which is quite full of any liquid, what do you know about the volume of the liquid which runs over, or is displaced? If the liquid is water, what do you know about the mass of the water which is displaced?

Counterpoise in one pan of your balance a dry beaker. Take a test-tube just wide enough to admit the solid (a glass stopper is a very convenient object to use for this experiment). Make a mark with a file on the test-tube, at such a height that when the stopper is in the test-tube it will be completely covered if water is poured in up to the mark.

Fill the test-tube up to the mark with water, carefully adjusting the level by means of a pipette. Then drop the stopper gently into the test-tube by inclining the tube and letting the stopper slide down so that no water splashes out of the test-tube. The water will now be above the mark. Transfer, by means of a pipette, all the water that has risen above the mark to the counterpoised beaker, and then weigh this water.

What is the mass of the water that has been displaced by the stopper?

What is the volume of this water, and therefore of the stopper?

Weigh the stopper.

Knowing the mass and volume of the stopper, calculate its density.

Would your result be equally trustworthy if you used a very wide test-tube? (See p. 14.)

Would you expect an equally accurate result if you filled

the test-tube to the brim and caught in the counterpoised beaker the water that ran over? Give reasons for your answer.

Experiment 17

To find the volume of an irregular solid which floats in water, *e.g.* a cork.

This is done in exactly the same way as in last experiment, the only difference being that a sinker must be used to keep the cork down, and *this sinker must be in the water each time that the level of the water is adjusted.*

For this purpose the sinker should be tied to a piece of cotton, by which it can be withdrawn from the test-tube and replaced when the cork is put in. An old 20 gm. weight, or the stopper of last experiment, makes a convenient sinker.

Weigh the cork and calculate its density.

Suggestions for alternative Experiments

In the same way as above described the following experiments may be performed:—

1. Find the volume of a piece of wire.

2. Find by displacement of water the volume of the cylinder used in previous experiments, and compare with the result of Experiment 11.

3. Find the average volume of a quantity of lead shot by finding the volume of say 100 of them and dividing the result by 100.

4. Find the volume of a block of beeswax (or of paraffin wax), and calculate its density.

Experiment 18

To verify the statement that the volume of a sphere is $\frac{2}{3}$ of the volume of the circumscribing cylinder.

By the circumscribing cylinder, we mean the cylinder (real or imaginary) into which the sphere would exactly fit. Thus the height and diameter of this cylinder must each be the same as the diameter of the sphere.

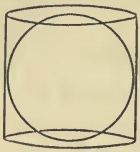

Fig. 23.

Find the volume of the sphere by displacement of water as in preceding experiments.

Find the diameter of the sphere, as in Experiment 5.

Then calculate the volume of the circumscribing cylinder, and find $\frac{2}{3}$ of the result. Write your account as follows:—

Volume of sphere by displacement of water	=	c.c.
Diameter of sphere	=	cm.
Radius of circumscribing cylinder $= r$.	=	cm.
$r^2 =$ sq. cm.		
$\pi r^2 =$ sq. cm.		
Height of cylinder	=	cm.
∴ volume of cylinder	=	c.c.
$\frac{2}{3}$ volume of cylinder	=	c.c.
Difference between volume by displacement and $\frac{2}{3}$ volume of circumscribing cylinder	=	c.c.

Examples

1. Find the volume of a sphere whose radius is 4.6 cms.

2. A sphere has a diameter of 5.2 cms. and weighs 95.6 gms. Find the volume of the sphere and the density of the material of which it is made.

3. The volume of a cone is one-third of the volume of a cylinder having the same base and height. Find the volume of a cone whose height is 8 cms., and the radius of whose base is 4.2 cms.

4. Find the volume of a cone whose height is 10 cms. and the diameter of whose base is 2.8 cms.

EXPERIMENT 19

To find the density of turpentine by specific gravity flask.

The specific gravity flask is simply a flask with a very narrow neck. In its most convenient form it has a stopper, ground so as to fit it accurately, and through this stopper a hole is bored. To fill it with any liquid, the liquid is poured in till it is near the top of the neck. The stopper is then put in, and any superfluous liquid escapes through the hole. The flask is then carefully dried on the outside, so that the liquid just fills the flask to the top of the stopper.

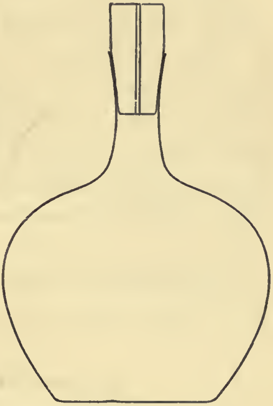

Fig. 24.

Counterpoise the flask when completely empty, then fill it with water, and weigh the water it contains. What is the volume of the flask?

Empty the flask, dry it and fill with turpentine, and weigh the turpentine it contains.

What is the volume of the turpentine whose mass you have found?

What then is the density of turpentine? Look back to the result obtained in Experiment 15, and say which of these methods you consider the more accurate, and why? (See p. 14.)

Can this method be used for finding the density of any liquid?

In Experiments 14 and 14A you found the weight of a known volume of turpentine and salt solution. What advantage is possessed by the specific gravity flask over the cylindrical vessel used in those experiments?

Experiment 20

To find the volume of a boxwood sphere by displacement of spirits of wine.

As the sphere sinks in spirits of wine, it is not necessary, in this case, to use a sinker.

Find the mass of spirits of wine displaced by the sphere exactly as in Experiment 16.

Then counterpoise an empty specific gravity flask and fill it with water, and thence find the volume of the flask.

Empty and dry the flask and fill with spirits of wine. How many grammes of spirits of wine are there in the flask? What is the volume of this mass of spirits of wine? What then is the volume of 1 gramme of the spirits of wine?

What is the volume of the spirits of wine displaced by the sphere and therefore the volume of the sphere?

Experiment 21

Find the internal diameter of a glass tube by finding the weight of water which it contains.

Counterpoise a dry beaker in one pan of your balance. Fill the tube full of water, and place this water in the counterpoised beaker.

What is the volume of the inside of the tube?

What is the length of the tube and therefore of the cylinder whose volume you have just found?

What is the area of cross section of the tube, *i.e.* the area of the base of the cylinder just mentioned?

What is the square of the radius of the interior of the tube?

What is the internal radius of the tube?

What is the internal diameter of the tube?

CHAPTER III

HYDROSTATICS

Experiment 22

To prove the Principle of Archimedes—*that when a body is immersed in a fluid it is buoyed up with a force equal to the weight of fluid which it displaces.*

Attach the short pan to your balance beam, and hang

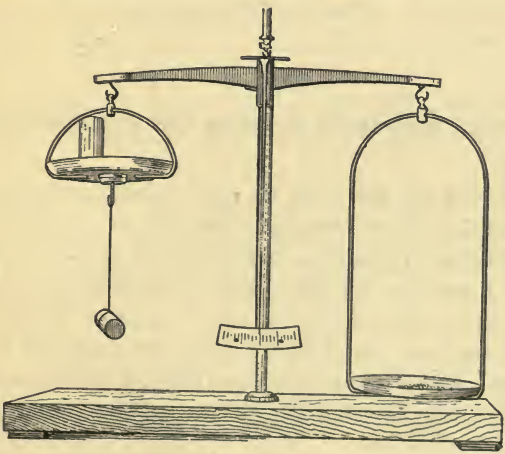

Fig. 25.

under it, by means of a single piece of cotton or horse hair, a metal cylinder, such as that used in previous experiments.

In the pan, above the cylinder, place a water-tight cylindrical case,[1] into which the metal cylinder exactly fits, and which therefore will contain just as much of any liquid as the cylinder will displace when completely immersed. Carefully adjust the balance by placing in the empty pan iron weights, shot, etc., till it is exactly even, and then bring up underneath the short pan a beaker of water, so that the metal cylinder is covered by the water.

What is the effect on the balance?

What does this prove as to the *direction* in which the fluid presses the cylinder?

Then fill the waterproof case exactly full of water and replace it in the short pan. If the Principle of Archimedes be true, the weight of the water which has been put into the case, being the same as the weight of water displaced, ought exactly to neutralise the upthrust of the water on the metal cylinder. State whether this is so.

* Experiment 23

Second experiment to prove the Principle of Archimedes.

Keeping the short pan on your balance, counterpoise if necessary, and then hang from the hook of the short pan a glass stopper by means of a short single thread of cotton. Weigh the stopper and then replace the weights in the box. As in last experiment, bring up a beaker of turpentine so that the stopper hangs in the turpentine when the balance is even. Weigh the stopper when hanging in the turpentine.

Why is the apparent weight now less than when stopper was hanging in air?

[1] This can easily be made by means of paper which is steeped in melted paraffin wax, the end being closed by a short cylinder of wood of the same diameter as the metal cylinder.

What is the *upthrust* on the stopper, *i.e.* the force with which the turpentine buoys up the stopper?

Next find the weight of turpentine which the stopper displaces by proceeding as in Experiment 16, only using turpentine instead of water.

In this case is the Principle of Archimedes true?

This experiment may be repeated with any other liquids such as alcohol, salt solution, etc.

Experiment 24

To find the volume of any solid that sinks in water (by Principle of Archimedes).

Using the short pan, counterpoise your balance as before, and then hang to it a glass stopper. Weigh the stopper while hanging in air. Then immerse it in a beaker of water and weigh again while in the water.

What is the upthrust of the water on the stopper?

What is the weight of water displaced by the stopper?

What then is the volume of water displaced by the stopper, and therefore the volume of the stopper?

Calculate the density of the stopper.

In comparing this method of finding the volume of a solid with that used in Experiment 16, which do you think the more capable of giving you an accurate result?

Examples

1. A stone weighs 64.52 gms. in air, and 36.04 gms. when immersed in water; find the volume of the stone.

2. A piece of iron weighs 142.8 gms. in air, and 123.6 gms. in water. Find the volume of the iron.

3. A certain body has a volume of 8.8 c.c., what will be the upthrust upon it when immersed (*a*) in water; (*b*) in a liquid whose density is .87 gms. per c.c.?

Experiment 25

To find the area of cross section and the diameter of a thin wire.

It is difficult to measure accurately the diameter of a thin wire by simply using a millimetre scale—to get an accurate result an instrument known as a screw wire gauge is generally used, but the following method, though tedious, gives accurate results when carefully carried out, and when a sufficient length of wire is available.

Take a piece of the wire about a metre long and, stretching it out straight, measure its length. Then coil it up and hang it to the short pan of your balance, and weigh it in air. Then weigh it in water.

What is the volume of the wire?

The wire being a cylinder of known height, you can calculate the area of the base of this cylinder and therefore the area of cross section of the wire.

What is this area?

Knowing the area of cross section, you can calculate the radius and diameter of the wire exactly as in Experiment 21.

Experiment 26

Find by Principle of Archimedes the density of a cork.

First, weigh the cork.

Hang to the short pan of your balance a sinker (an old 20 gm. brass weight is convenient for this purpose) which when attached to the cork will sink it in water. Bring up a beaker of water so as to immerse the sinker, and place the cork in the short pan above the sinker and counterpoise. Then, leaving everything else

exactly as before, fasten the cork to the sinker, so that instead of being in air the cork is now immersed in water,

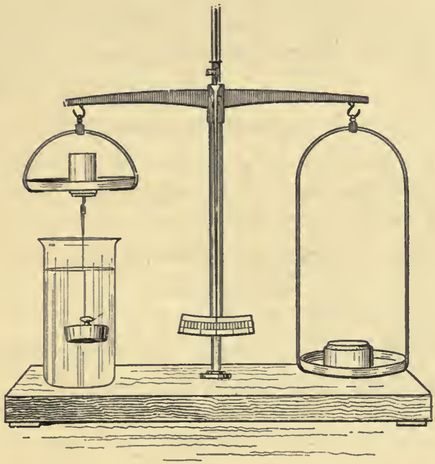

Fig. 26.

and is accordingly buoyed up by the water. Place weights in the short pan to restore equilibrium.

What is the upthrust of the water on the cork?

What is the volume of the cork?

Thence calculate the density of the cork.

Experiment 27

To find by Principle of Archimedes the density of a solid which is soluble in water. (See p. 13.)

Weigh the solid. Find, by Principle of Archimedes, the upthrust in a liquid which does not dissolve the solid, *e.g.* if the solid is a crystal of copper sulphate, use a saturated solution of copper sulphate or turpentine.

This gives the weight of the liquid which is displaced by the solid.

By means of a specific gravity flask, find how many grammes of the liquid fill the flask; then find the volume of the flask by weighing the water it contains, as in Experiment 19.

Then answer the following questions:—

What is the volume of 1 gramme of the liquid?

How many grammes of the liquid are displaced by the solid?

What then is the volume of this quantity of liquid?

What is the volume of the solid?

What is the density of the solid?

Why could the experiment not be done at once by finding the upthrust of water on the solid?

Experiment 28

To find the density of a liquid by Principle of Archimedes.

Counterpoise your balance with short pan as before. Hang to it a glass stopper and weigh it in air.

Weigh the stopper while hanging in water. Then weigh the stopper while hanging in the liquid (*e.g.* solution of copper sulphate).

What is the upthrust on the stopper in water?

What is the volume of the stopper, and therefore the volume of any liquid displaced by it?

What is the upthrust on the stopper in the liquid?

What is the weight of liquid displaced by the stopper?

What is the volume of this liquid?

What then is the density of the liquid?

EXPERIMENT 29

To prove that when a body floats in a liquid the weight of the liquid displaced by the body is equal to the weight of the body itself.

Place an empty beaker in one pan of your balance and counterpoise it.

Place some shot in the bottom of a narrow test-tube, so that the test-tube will float upright when placed in water.

Then take a wider test-tube and fill it quite full of water, hold it over the beaker, which you have previously counterpoised, and lower gently into the wider test-tube the narrow weighted one until it floats. The result of this will be that a certain quantity of water has overflowed into the beaker, and this is the water which has been displaced by the floating test-tube. Replace the beaker in the balance and place the smaller test-tube in the other pan.

State the result, and say what is the relation between the weight of water displaced by the test-tube and the weight of the test-tube itself.

Measure roughly the depth to which the test-tube floats in the water, and keep the same test-tube and shot for use in next experiment.

EXPERIMENT 30

Repeat the above experiment, using a solution of common salt instead of water.

Does the test-tube sink deeper in water or in salt solution? What do you know about the weights of water and of salt solution displaced by the floating test-tube?

Does the same weight of water or of salt solution occupy the greater volume? Which of the two liquids is therefore the denser?

EXPERIMENT 31

To make a hydrometer and find by its means the density of turpentine.

In the small test-tube of Experiments 29 and 30 place the graduated strip of cardboard which is given to you. This strip is graduated in centimetres and millimetres like your metre measure, and the "o" on the scale is at one end of the cardboard. Pour shot into the test-tube, so as to make it float with about 4 cm. out of water. Take care that the "o" on the cardboard scale comes about half-way down into the curved bottom of the test-tube, so as to allow for the narrowing of the tube at the bottom. (See Fig. 27.) You now have a hydrometer.

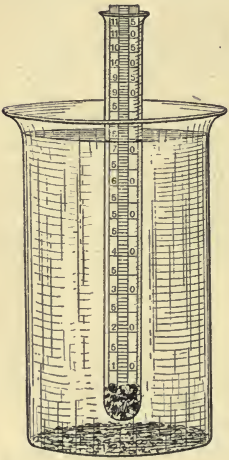

Fig. 27.

Let the hydrometer float in water, and note as accurately as possible the depth on the scale to which it sinks in water; this is most accurately done by looking *under* the surface of the water.

Then place it in turpentine and again note the depth to which it sinks.

Why does it sink deeper in turpentine than in water?

What do you know about the weights of water and turpentine displaced by the hydrometer?

What is the ratio of the volumes of these liquids displaced by the hydrometer?

What then is the density of turpentine?

To what depth would the hydrometer sink in a liquid whose density is 1.2 gm. per c.c.?

Experiment 32

Cartesian Diver.

This consists of a glass tube about 4 cm. long, open at one end and having a bulb blown at the other. It is weighted by wrapping some wire round the tube near the open end, so that it may just float in water with the open end downwards.

Place it in a tall jar nearly full of water, and stretch a sheet of indiarubber over the mouth of the jar and fasten it so as to be air-tight. Press in the indiarubber and it will be found that the tube sinks, and on relieving the pressure it will probably ascend to the surface again.

You will understand clearly the reason of this if you carefully observe the water inside the tube when you press on the indiarubber, and when you relieve the pressure.

What happens to the water inside the tube when the indiarubber is pressed?

Then answer the following questions:—

Pressing on the indiarubber diminishes the *space* occupied by the air above the water in the jar, what is the immediate effect of this on the water? (See p. 52.)

What is the effect of this on the air inside the diver?

What is the effect on the weight of water displaced by the diver, and therefore on the force with which the diver is buoyed up by the water?

Explain therefore why pressing on the indiarubber causes the diver to sink.

Sometimes the diver remains at the bottom of the jar, even when the pressure on the indiarubber is removed. Can you explain this?

Pressure exerted by a Liquid

* Experiment 33

A liquid always exerts pressure at right angles to the surface on which it is pressing.

Take a tin can with a hole about 1 mm. in diameter bored in its side close to the bottom of the tin. Close this hole with the finger and fill the can with water, on removing the finger the water rushes out through the hole. The direction of the jet just as it leaves the side of the vessel gives the direction of the pressure at that point. Note this direction when the tin is turned with its side in different positions, drawing diagrams in your note-book to illustrate the experiment.

* Experiment 34

The pressure exerted by a liquid at any point is the same in all directions.

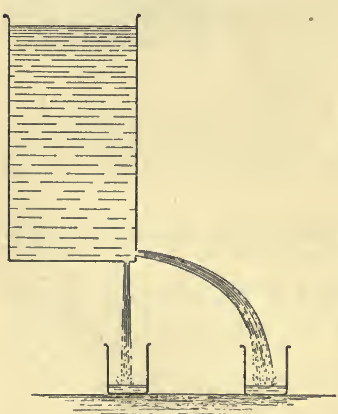

Fig. 28.

Take a vessel, as in last experiment, with two holes about 1 mm. diameter bored close together, one in the side and one in the bottom of the vessel as in diagram. Care should be taken that the holes are as nearly as possible of exactly the same size. Close the holes with the finger and thumb and fill the vessel full of water. Then let a companion hold two beakers so as to catch

the water escaping from each hole. When the water has sunk a few centimetres in the vessel, close the two holes again as before.

Weigh the water collected in each beaker and record the result, explaining clearly whether the statement at the beginning of this experiment is true.

Experiment 35

To measure the pressure of the gas supplied to the laboratory.

Place in a U-shaped tube a quantity of water so as to reach about half-way up each side of the tube. Attach

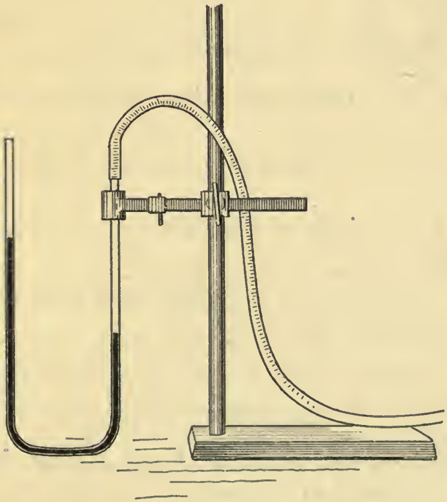

Fig. 29.

one limb of the U to the gas nozzle by means of an india-rubber tube, and turn on the tap. Measure the height of the surface of the water in each limb of the U tube above the table.

Why is the water at a higher level on one side of the U than on the other?

What depth of water would be required to be poured into the tube on the right-hand side in order to maintain the level of the water on the left if the right-hand side were open to the air?

What depth of water would therefore be required to produce the same pressure as that exerted by the gas?

What pressure does this column of water exert on 1 sq. cm. at its base?

What pressure then does the gas exert on every square centimetre of the pipes in which it is contained?

Experiment 35a

Repeat the experiment, using turpentine instead of water.

What depth of turpentine produces the same pressure as the gas?

Why is the depth of turpentine greater than that of water?

What conclusion do you draw from this as to the density of turpentine?

Experiment 36

To compare the densities of two liquids which do not mix, by means of a U tube.

Pour water into a U-shaped tube till it reaches a level rather less than half-way up each side. Then pour turpentine gently into one limb of the U till the common surface of water and turpentine is a few centimetres above the bend as in the diagram.

Measure and record the vertical height of

(1) the surface of the water;

(2) the surface of the turpentine;

(3) the common surface of water and turpentine; above the table.

What is the depth of turpentine?

What depth of water would be required to produce the same pressure, *i.e.* what depth of water above C would maintain the level of the water at A?

How many times denser or less dense is turpentine than water, *i.e.* what is the ratio (see p. xvi) of the density of turpentine to the density of water?

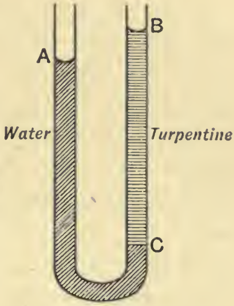

Fig. 30.

* Experiment 37

To find the density of a liquid which mixes with water by means of U tube.

If the liquid mixes with water there will be no distinct surface of separation between the two liquids. But the same method may still be employed if we first pour into the U tube a quantity of mercury sufficient to fill the bend of the U. Mark carefully, by means of strips of gummed paper, the position of each surface of the mercury on the tube, and then pour into one limb alcohol and into the other water, until the surfaces of the mercury are at the marks. Then we know that the pressure exerted by the water is equal to that exerted by the alcohol.

In this way calculate the density of alcohol.

* Experiment 38

To find, by means of inverted U tube, the density of a liquid which mixes with water.

Take two glass tubes about 80 cm. long, open at both ends, and join them by means of an indiarubber 3-way tube as in the diagram, the open branch of the 3-way tube being fitted with a clip by which it may be closed air-tight.

Place the ends of the glass tubes in beakers one containing water, and the other the liquid whose density is required — say alcohol, and draw the liquids up the tubes by sucking at the open end of the 3-way tube till the alcohol is within a few inches of the top.

Measure the height of the liquid in each tube above the liquid in the beaker, and record the result.

What do you know about the pressures at the surfaces of the liquids in the beakers?

What do you know about the pressures at the surfaces of the liquids in the tubes?

What is the relation between the pressures exerted by the two columns of liquid?

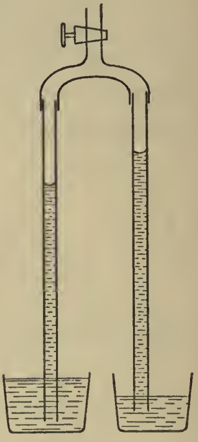

Fig. 31.

What then is the relation between the densities of the liquids, *i.e.* what is the ratio of the density of alcohol to that of water?

Note.—The two tubes should be clamped to the same retort-stand.

Experiment 39

To make a barometer.

A barometer is an instrument for measuring the pressure of the atmosphere.

Take a stout glass tube about a metre long and at least 5 mm. internal diameter and closed at one end. Fill with clean mercury up to within about a centimetre of the top. Close the open end with the finger and gently invert the tube. A large bubble of air will travel up the tube, sweeping up the small bubbles that adhere to the glass. Repeat this until all the small air-bubbles have been removed, and then fill the tube up to the top with mercury. Close the end of the tube tightly with the finger once more and invert the tube, placing the end covered by the finger below the surface of mercury in a small bowl. Remove the finger and note what happens.

Clamp the tube in your retort-stand so as to be vertical, and measure the height of mercury in the tube above the mercury in the bowl.

Why does not the mercury all run out of the tube?

What is the pressure on the top of the mercury in the tube?

What pressure does the mercury in the tube exert on 1 sq. cm. at a point on a level with the surface of mercury in the bowl? (Density of mercury = 13.6 gm. per c.c.)

What pressure does the air exert on the surface of mercury in the bowl?

What would be the effect of using a wider tube?

What is the effect of tilting the tube so as to be at an angle with the vertical?

What would be the effect of making a small hole in the tube above the mercury?

(Do not try to make a hole in the tube, but simply state what you would expect to happen if the hole were made).

Note.—This, and all other experiments in which mercury is employed, should be performed over a shallow tray to catch any mercury which may be spilt accidentally. Small wooden trays about 30 cm. long, 25 cm. wide, and 2 or 3 cm. deep will be found convenient.

Boyle's Law

It is a matter of common observation that if the volume occupied by a given quantity of gas is diminished, the pressure which it exerts is increased, other things being the same. For example, in the common pop-gun, it is the increase in pressure of the air enclosed between the cork and the plug which is forced in, due to the diminution in volume of this air, which expels the cork with a small explosion.

The numerical relation between the volume occupied by a gas and the pressure which it exerts is given in a statement which is known as Boyle's Law, from the name of its discoverer, and which may be expressed as follows :—

"The pressure exerted by a given mass of gas at constant temperature is inversely proportional to the volume which it occupies."

To prove this law, therefore, we require to alter the volume of a certain quantity of gas and note the pressure exerted by it at each known volume, taking care that the temperature of the gas does not alter in the meantime. Knowing the pressure of the gas and its volume in each case, we can test whether the one quantity is inversely proportional to the other by the method described in the introduction, p. xvii.

EXPERIMENT 40

To prove the truth of Boyle's Law.

Take the apparatus, as shown in the diagram, where AB is a glass tube closed at A and graduated in cubic centimetres from A downwards. BC is a piece of strong indiarubber tubing joining AB to CD, a tube of the same diameter but open at both ends and about 80 cm. long. The indiarubber tubing should be firmly bound to the glass tubes by string or wire. Fix AB and CD in your retort-stand, so that both glass tubes are vertical, having first poured in mercury enough to fill the tube BC. Adjust this mercury so that the surfaces of mercury in the two tubes may be at the same height above the table. This can be done by removing the tubes from the clamps and allowing some of the air in AB to bubble up through the mercury by lowering the tube AB as in Fig. 33.

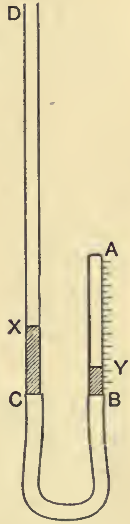

Fig. 32.

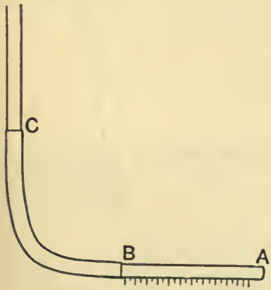

Fig. 33.

The final adjustment can be made by raising or lowering AB until the two mercury surfaces are at the same height above the table, which we may assume to be horizontal.

Read the height of the barometer and record it. Then read and record the volume of the air in AB.

What is the pressure exerted by the air in AB?

Keeping the tubes fixed in the retort-stand pour more

mercury into CD, and then note the volume of the air in AB.

Measure the height of the mercury in the open tube above that in the closed, and record it.

What is the pressure exerted by the air in AB now?

Repeat this operation four or five times until the mercury in CD is near the top of the tube, and draw up a table like the following :—

	Volume. c.c.	Difference in Level of Mercury Surfaces. cm.	Pressure. (cm. of Mercury.)	Volume × Pressure.
1st Expt.				
2nd Expt.				
3rd Expt.				
4th Expt.				
5th Expt.				
6th Expt.				

If Boyle's Law is true, what would you expect to find with regard to the last column of above table? (See p. xvii, Inverse Proportion.)

Does your experiment prove the truth of the law? Was the temperature constant?

PART II

HEAT

CHAPTER I

EXPANSION

Experiment 1

Does iron expand when heated?

You are supplied with a rod of iron (the rod of a retort-stand will do very well), a piece of straw about 20 cm. long,

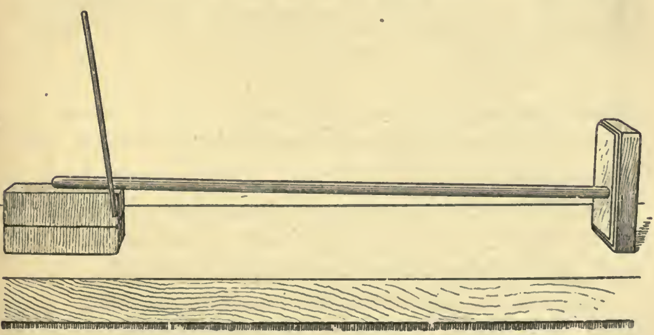

Fig. 34.

a pin, and some blocks of wood. Pass the pin through the straw a few centimetres from one end. Lay the rod on

some blocks of wood, as in Fig. 34, one end resting on the pin as on a roller, the straw being vertical.

Then heat the rod with a Bunsen burner, notice the effect and say what you conclude as to the effect of heating the bar of iron. Allow the bar to cool, note the behaviour of the straw and say what is the effect on the length of the bar of cooling it.

Question 1. Would it be safe in making a railway to lay the rails so that their ends were in contact?

Question 2. Do you know of any other cases in which this property is either allowed for or made use of?

Question 3. Why does glass often crack when heated? If you are obliged to heat a glass vessel, what is the best way to avoid this danger?

Experiment 2

Do all substances expand by the same amount when heated equally?

Take two wires, iron and copper, about .05 cm. thick and about a metre long. Fasten them side by side so as to stretch horizontally above the table at a height of 30 or 40 cm., as in Fig. 35. (It will be found convenient in clamping them to use a small piece of wood to prevent the sharp edge of the clamp from cutting the wires. It is also an advantage to fix the retort-stand to the table by means of a carpenter's clamp instead of using weights as shown in Fig. 35.) To the middle of each wire hang a small lead weight—about 20 gm. will be sufficient.

Measure the height of each wire above the table. Then while one keeps the metre scale vertical and ready to measure the height of each wire, let the other heat both wires equally with the Bunsen flame. During this operation care must be taken to keep the flame moving back-

wards and forwards along the wires, otherwise, if the flame is kept still at any one point, the wires may be melted. Care must also be taken to heat both wires as equally as

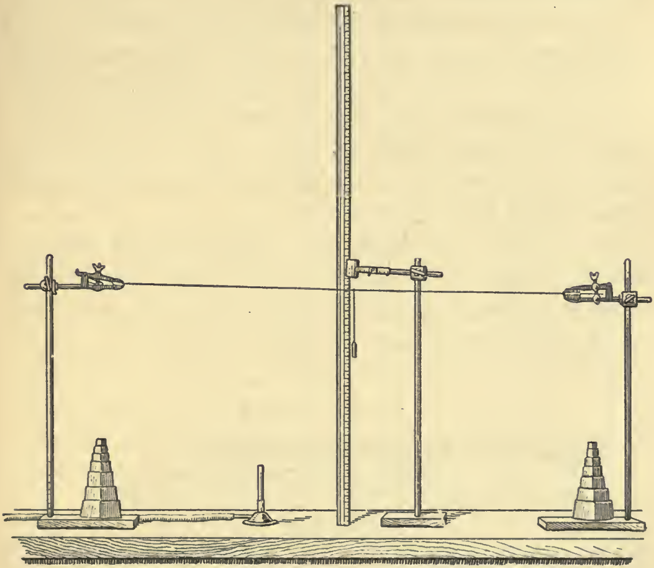

Fig. 35.

possible. Note the heights of the middle points of the two wires when equally hot, and enter your results thus:—

Height of middle of iron wire before heating = cm.
Height of middle of iron wire after heating = cm.
∴ middle of iron wire has dropped cm.
Height of middle of copper wire before heating = cm.
Height of middle of copper wire after heating = cm.
∴ copper wire has dropped cm.

What conclusion do you draw from this experiment as to the effect of heating equally two rods of iron and copper which were originally of equal length?

Experiment 3

Compound bar.

Cut out two strips of cardboard about 1 cm. wide, and make one about 10 cm. long and the other 1 mm. shorter than the first. Place them side by side, and arrange them so that they touch each other at every point, the two strips having their ends exactly together. You will find that to do this you must bend them into a curve, the shorter strip being on the inside of the curve.

If you had two strips, one of iron and the other of copper, riveted or brazed together side by side so that they could not separate from each other, what would you expect to happen when the compound bar is heated?

Experiment 4

Expansion of liquids—Thermometer.

A mercurial thermometer consists essentially of a small glass bottle with a very long and narrow cylindrical neck, the neck is furnished with a scale by which the position of the surface of the mercury in the neck can easily be noted. When the mercury in the thermometer is hot it takes up more room in the bottle, and so stands at a higher point of the neck than when it is cold. The bottle is called the *bulb* of the thermometer, the neck is called the *stem*, and the divisions on the stem are called *degrees*. In the thermometers which are generally used in laboratory work, these degrees are called centigrade degrees, to distinguish them from the divisions on the scale of many thermometers which are used for domestic purposes, and which are called Fahrenheit thermometers.

Thus, if on looking at the thermometer stem we see that the top of the mercury is at the mark "35" on the

stem, we say that the temperature of the thermometer (and of anything with which it is in contact) is "35 degrees centigrade," or, as it is generally written, 35° C.

You will see later on (Experiments 16 and 23) how this scale is obtained—at present, all that is necessary to notice is that the hotter a body is the higher will the mercury rise in a thermometer which is in contact with that body.

To get an idea of the temperature, as indicated by a thermometer, take a beaker of cold water and heat it, keeping your thermometer immersed in the water. Try the temperature of the water by means of your fingers, when the thermometer stands at 20° C., 40° C., and 60° C., and describe the result in your note-book. Then place the bulb of the thermometer in your mouth and keep it there for about five minutes, and then let some one read the height of the thermometer while the bulb is still in your mouth, and note the result.

Points to be noticed in reading the temperature of anything by means of a thermometer.

1. The eye should be in such a position that the line joining the eye and the surface of the mercury is at right-angles to the scale. This is to avoid parallax. (See p. 4.)

2. The thermometer must be read while it is in contact with the thing whose temperature is required. It must not be removed and then read, as is often done. If it is not in a convenient position for being clearly read, the body whose temperature is required may be moved *along with the thermometer*, but the reading must be taken with the thermometer in contact with, and as far as possible surrounded by, the thing whose temperature is being observed.

3. When the temperature of any body is being noted, time must be given for the thermometer to reach the same temperature as the body. Thus, if we wish to note the temperature of a liquid, the thermometer must be left in

the liquid until the surface of the mercury has ceased to move.

For the same reason, a thermometer does not at any instant give the true temperature of the body with which it is in contact if that body is either rising or falling in temperature, unless the rise or fall is very slow. Thus, if we place a thermometer in a liquid which is being heated, the temperature of the thermometer will always be a little lower than that of the liquid, because the heat has first to pass into the thermometer from the liquid before the temperature of the thermometer rises.

Experiment 5

Does water expand equally for the same rise of temperature at all temperatures?

To answer this question we must find out how much a given quantity of water expands for a given rise of temperature.

You are supplied with a small glass flask having a volume of about 3 c.c., a piece of glass tubing with bore about 1 mm. in diameter and about 30 cm. long, and of such external diameter that it can pass easily into the neck of the flask, and a piece of indiarubber tubing about 2 cm. long.

Construction of apparatus.—Fill the flask with cold water, and placing the indiarubber tubing round the glass tube at one end (the end marked zero, if the tube is graduated), fit it into the neck of the flask with a slight screwing motion, being careful to see that no air bubble is left in the flask. If there is, the operation must be repeated. The glass tube should then be pushed downwards with the same screwing motion until it reaches to near the bottom of the flask. The result of this will be that the

water displaced by the tube will run out at the top of the tube. Then withdraw the glass tube slightly, until the surface of the water in the tube is about 2 cm. above the neck of the flask.

If the tube is graduated in centimetres and millimetres this is all that is wanted, but, if not, a scale divided into millimetres or similar small divisions must be attached to the tube by means of indiarubber bands (an old thermometer stem answers very well for the purpose). It is important that this scale should be always in the same position with respect to the tube, and for this purpose it is convenient to make a mark on the tube with a file and adjust the scale, so that this mark is always opposite to the same graduation on the scale. By far the most convenient arrangement, however, is to have the tube graduated in millimetres.

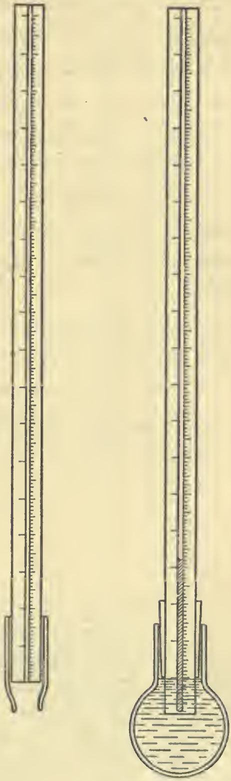

Fig. 36.

Mode of conducting the experiment.—The flask, tube, and scale thus fitted together are now placed in a beaker half-full of small pieces of ice, along with a mercury thermometer, until the whole is at a steady temperature, *i.e.* until the surface of the water in the tube ceases to fall or rise. Then note the position of the surface of the water on its scale and the temperature as indicated by the thermometer.

Turn out the ice and fill the beaker with cold water,

and replace thermometer and flask, etc., as before, continually stirring the water with your thermometer. Adjust the temperature of the water till it is about 10° C., by heating it if it is below that temperature, or by adding ice if it is above it. Again note the position of the water in the tube on its scale, when the water in the tube has stopped rising or falling. Heat the beaker of water until its temperature is 20° C., and while it remains steady at this temperature note the height of the water in the tube. Repeat this for temperatures of 30°, 40°, 50°, 60°, etc., until the water runs out at the top of the tube, or until it boils.[1]

All your observations should be written down in a table like the following:—

Temperature.	Position of Water Surface.	Expansion for 10° C.	Average Expansion for 1° C.
0			
10			
20			
...			
...			

The third column gives the expansion for 10° C., *i.e.* the distance through which the surface of the water rises when heated through 10° C.; the fourth column gives the average expansion for 1° C., *i.e.* one-tenth of the expansion for 10° C.

[1] The temperature of the beaker of water can be adjusted either by heating the water with a Bunsen burner, and removing the burner when the required temperature has been reached, or turning it down very low, or else by pouring in some hot water, after having poured out some of the colder water. The latter is the more troublesome, but perhaps the more expeditious method. In any case, care must be taken that the temperature is quite steady for two or three minutes before the position of the water surface is noted.

1. From this experiment, what answer would you give to the question at the beginning of this experiment?

2. If water does not expand by the same amount for the same rise of temperature at all temperatures, does it expand more or less for a rise of 1° C. as the temperature becomes higher?

3. If a certain quantity of water expanded 1 c.c. in rising from 0° C. to 30° C., how much would it expand on being raised from 30° C. to 60° C.?

4. If you had used a larger flask with the same tube, what difference would that have made in the rise of the surface of water in the tube for a given rise in temperature?

5. If (the flask being the same) a narrower tube had been used, what would have been the effect on the rise of water in the tube for a given rise of temperature?

6. If you wished to obtain a large movement of the liquid in the tube for a small rise in temperature, what would you do?

* Experiment 6

Expansion of turpentine.

To compare the expansion of turpentine with that of water for temperatures between 10° C. and 80° C.

Use the same apparatus as in last experiment, and fill in exactly the same way with turpentine. Note the height of the surface of the liquid at temperatures 10° C., 20° C., etc., and write down your results in tabular form thus:—

Temperature.	Position of Surface of Turpentine.	Expansion for 10° C.	Expansion for 1° C.	Expansion of Water for 1° C.
10				
20				
30				
etc.				

1. Does turpentine expand uniformly, *i.e.* does it expand by the same amount for the same rise of temperature at all temperatures?

2. If not, does it expand more or less for a rise of 1° C. as the temperature rises?

3. Whether does water or turpentine expand the more when its temperature rises through 1° C.?

4. Is it necessary to use the same flask and tube for both experiments?

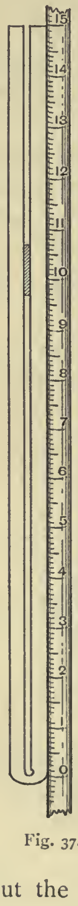

Fig. 37.

* Experiment 7

Expansion of air.

You are supplied with a glass tube with bore about 1 mm. in diameter, closed at one end, and containing dry air separated from the outside air by a drop of mercury. Attach to this tube, by means of indiarubber bands, a scale of millimetres or other small divisions — the same scale as was used in the last two experiments is very suitable. Adjust this scale so that the "0" or zero on the scale is at the bottom of the inside of the air tube.

In this way we can read off the volume of the imprisoned air by noting the position on the scale of the lower end of the mercury drop.

Place this apparatus, with the closed end downwards, along with a thermometer in a beaker deep enough to rise well above the mercury drop. Place small pieces of ice round the apparatus, and when the temperature is at 0° C. read off the volume of the air. Turn out the ice, and put water in the beaker, and note the volume of the air at 10° C., 20° C., etc., up to 100° C.

As the mercury drop is apt to stick, it is well to tap the tube before taking a measurement.

Arrange your results in tabular form thus :—

Temperature.	Volume of Air.	Expansion for 10° C.	Expansion for 1° C.

1. Does air expand uniformly, *i.e.* does it expand by the same amount for the same rise of temperature at all temperatures? If not, does it expand more or less as the temperature rises?

2. What is the average amount of expansion for a rise of 1° C.?

3. What fraction of the volume at 0° C. is this? Answer in decimals to 3 significant figures.

* **Coefficient of expansion.**—*The fraction of its volume at 0° C., through which a body expands when its temperature is raised by 1° C., is called the coefficient of cubical expansion of the substance of which the body is composed.*

Thus the coefficient of cubical expansion is a property of a substance, and not of a particular body, just as in the case of density. To find the coefficient of expansion we thus require to know (*a*) the volume of a certain quantity of the substance at 0° C.; (*b*) the volume of the same quantity at some other known temperature. From this we can find the average increase in volume for a rise of 1° C. in temperature, and dividing by the volume at 0° C. we get the coefficient. Thus in Experiment 7 the coefficient of cubical expansion of air is the answer to question 3.

It will be noticed that in the case of substances, such as water and other liquids, which do not expand uniformly, it is not, as a rule, accurate to deduce the expansion for a rise of $1°$ C. from the expansion for a greater rise in temperature. In these cases, in fact, the coefficient of expansion is different at different temperatures. In order to find the coefficient of cubical expansion for water at say $20°$ C., we should find the volume at $0°$ C. of a given mass of water, and then its increase in volume as it is heated from $19\frac{1}{2}°$ C. to $20\frac{1}{2}°$ C. Then the coefficient of cubical expansion will be the observed increase in volume from $19\frac{1}{2}°$ C. to $20\frac{1}{2}°$ C. divided by the volume at $0°$ C.

Any of the experiments just performed (Experiment 6) could be used for finding the coefficient of cubical expansion of any liquid, if we knew the volume of the bulb and of each millimetre of the stem.

* Experiment 8

Draw curves showing the expansion of water, turpentine, and air.

On a sheet of squared paper draw two pencil lines along two of the heavy lines at right angles to each other near the edge of the paper, as in Fig. 38. Along the horizontal line (axis of abscissæ) mark each heavy vertical line with the figures 10, 20, 30, 40, etc.; from left to right, beginning with 0 at the intersection of the two pencil lines. Take these numbers to represent degrees centigrade.

Similarly, on the vertical pencil line (axis of ordinates), mark numbers from the bottom upwards. Instead of making the lowest one "0," you may find it more convenient to make it some other multiple of 10, depending on the scale which you have used for your tube. For example, if you used a scale on which the lowest reading

is 23, you should make the lower end of your vertical line 20, the next thick line 30, and so on. These numbers will correspond to the divisions on your scale, and therefore the volumes of the substances whose expansion was being observed.

With a sharp-pointed pencil make a small cross on the axis of ordinates at that point on it which represents the position of the water in Experiment 5; when the tem-

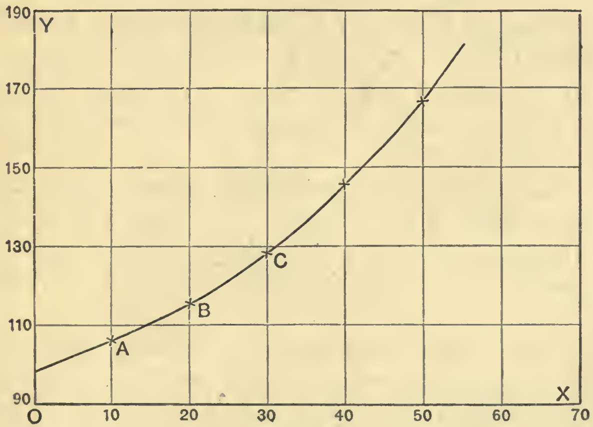

Fig. 38.

perature was 0° C. Make a similar mark on each of the vertical lines passing through 10, 20, etc. on the horizontal axis. Thus the height of the cross above the horizontal axis represents the volume of the water in the flask and tube at the temperature indicated on the horizontal axis.

Having drawn a cross for each measurement taken in Experiment 5, draw *freehand* a pencil line so as to pass through these crosses, or at least to pass very near them. The line should be quite smooth—whether it is straight or curved.

Do the same to represent the measurements of Experiment 6 and of Experiment 7 on the same sheet of paper.

Write down, in your own words, a description of each of the three lines thus drawn, saying whether they are straight or curved, whether the curvature seems to be regular or irregular, concave upwards or concave downwards.

Experiment 9

Change of density of a substance due to change of temperature.

If a substance expands when it is heated, will the density of the substance be greater or less when it is hot than when it is cold?

As a result of your previous experiments, state whether water is denser or less dense at 60° C. than it is at 20° C.?

If some water at 60° C. is introduced into the middle of a quantity of water at 20° C., will the warm water rise or sink?

To verify your answers, try the following experiment. Take a small beaker and fill it almost half-full of cold water. Cut out a circular piece of paper, just large enough to float on the surface of the cold water without catching in the sides of the beaker.

Heat some water in another beaker, and gently pour it on to the surface of the paper. This is easily done by holding the thermometer to the edge of the beaker when pouring out the water, as in Fig. 39; the water runs down the thermometer, and so does not splash. In this way fill the beaker up to the top with hot water, and then remove the paper gently.

Take the temperature of the water at the top of the beaker, and then the temperature of the water at the bottom, and record your results.

Explain why the temperatures are different. If you poured cold water on the surface of hot water, what would be the result?

Fig. 39.

What is the use of the paper in this experiment, *i.e.* what would probably happen if you poured the hot water into the cold without the paper?

Explain the reason why it was important in Experiments 5, 6, and 7 to keep the water in the beaker well-stirred.

CHAPTER II

CONVECTION, CONDUCTION, AND RADIATION

Experiment 10

Convection currents in water.

Take a fairly large beaker, holding about 400 cc., and fill it nearly full of cold water; stir into it a few grains of fine sawdust, and heat it with a small flame by means of your Bunsen burner, taking care that the burner is well to one side of the beaker. Notice the behaviour of the sawdust, and state what you believe to be the complete explanation of it.

Take the temperature of the water at the top and bottom of the beaker, and see whether the temperature is nearly the same at the two places.

Would you expect the water to become equally heated all over if you heated it at the top and not at the bottom? Give reasons for your answer.

Test the accuracy of your views by heating a test-tube of water at the top, as in Fig. 41. The glass above the water should not be much heated else it is liable to crack; the flame—a small one—should be made to play just below the surface of water.

After heating the water in this way remove the flame, and move your finger up the outside of the test-tube, and

see whether the water or glass is heated below where the flame touched it.

Take the temperature of the water at top and bottom, and record the results.

In the first case the currents of water which you

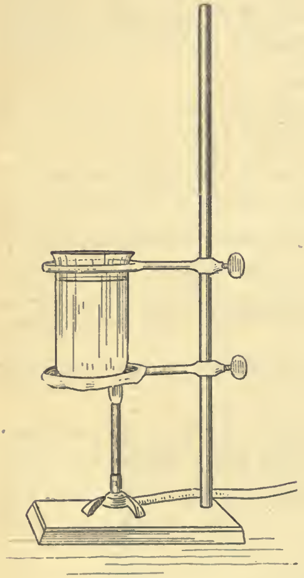

Fig. 40.

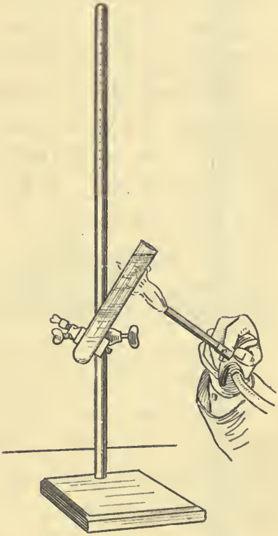

Fig. 41.

observed are called *convection* currents, because the heat is conveyed by them to the whole of the water.

Were there any convection currents in the second case?

What, then, is the essential point of difference between the two cases?

Why could not heat be carried through a solid body in the same way as it was carried through the water in the first case, *i.e.* when the water was heated at the bottom?

Conduction of Heat

In last experiment, when the water was heated at the bottom, the heat was carried from the bottom of the beaker to the rest of the water by means of convection currents, and the process is called *convection* when heat is carried from one place to another by heated particles moving and so carrying the heat with them.

Heat may also be carried from one place to another by *conduction*, *i.e.* each particle of the body which is heated hands its heat to the next, and so on, although the particles keep their places. Thus, when a poker is placed with one end in the fire, the other end becomes heated in this way. Also the heat is carried in the same way through the iron of a kettle when it is placed on the fire, from the fire to the water inside the kettle.

Judging from last experiment would you say that water is a good conductor of heat?

From your own experience, say which of the following substances are good conductors of heat: wood, iron, glass, silver; describing the observations on which you base your answer in each case.

Experiment 11

How does the conducting power of a solid, such as a rod or wire, depend on its thickness?

To answer this question take two iron wires about 15 cm. long, one thicker than the other (.4 cm. diameter and .2 cm. diameter are suitable sizes). Clamp them side by side in the clamp of your retort-stand, so that they are about 2 cm. apart at the clamp, and touching each other at the other end, as in Fig. 42.

Place the ends which touch each other in your Bunsen flame, and place your fingers on the wires close to the clamp. You will notice that for a short time each wire becomes steadily hotter, but soon a time is reached after

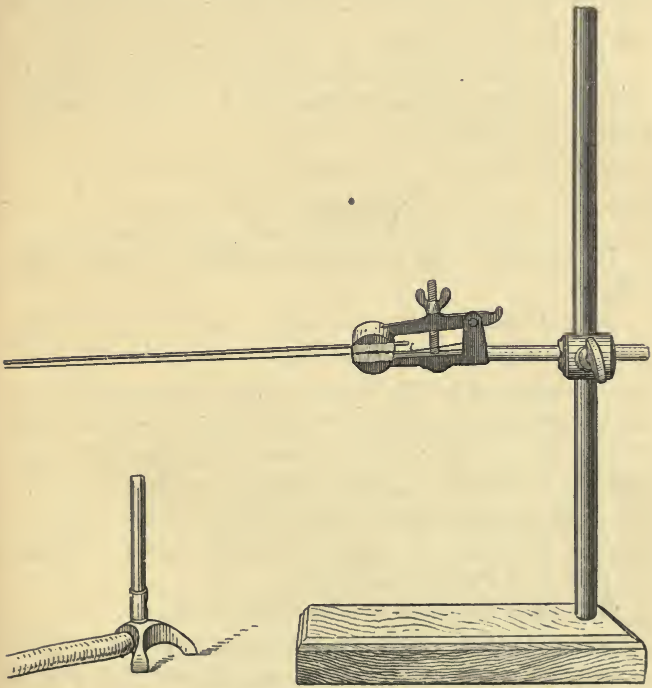

Fig. 42.

which no rise of temperature takes place. When this is the case the wires are said to have reached the *stationary state.* Note which of the two becomes the hotter at the clamp.

Move your fingers slowly along the two wires towards the flame; what do you notice as to the temperature of each wire? Keeping your two fingers, one on each wire,

at the same distance from the ends of the wires, state which of the two is the hotter.

What conclusion do you draw from this experiment as to the effect of thickness on the conducting power of a rod, *i.e.* on the amount of heat which can be conducted along it in a given time?

What do you conclude as to the effect of the length of the rod on the amount of heat which can be conducted along it in a given time?

Experiment 12

To compare the conducting powers of iron and copper.

First Method.—Take two wires, one of iron and the other of copper, of the same length and thickness (about 20 cm. long and .4 cm. thick). Clamp them together, as in last experiment, with the outer ends touching each other. Heat these outer ends with the Bunsen flame, and, after the stationary stage has been reached, find out which wire is the hotter at equal distances from the hot ends.

What conclusion do you draw as to the relative conducting powers of the two substances?

Why must the wires be of the same thickness?

Second Method.—Take the same two wires held in the retort-stand, clamp exactly as before, only instead of placing your fingers on the wires take a safety match, and, placing its head in contact with one of the wires near the clamp, move it slowly towards the flame, keeping it in light contact with the wire. Note the distance from the clamp to the point at which the match ignites. Do this three times for each wire.

Remove the flame, and measure the distance of the hot end from the clamp, and thus find how far from the hot

end in each case was the point at which the match ignited.

Then find the average distance from the hot end of the copper wire of the point at which the match ignited, and the same for the iron wire.

What do you know about the temperatures of the two wires at the points where the match is ignited?

What, then, do you conclude as to the relative conducting powers of iron and copper?

Note that in the first method we compare the temperatures at two points at the same distance from the hot end, in the second we compare the distances from the hot ends at which the temperatures are the same.

Radiation

We have seen that heat can be carried from one place to another by convection, *i.e.* by the heated particles moving and carrying the heat with them, and by conduction, *i.e.* by the heated particles passing on heat to the colder particles near to them. The first of these methods can only take place in a fluid, *i.e.* a liquid or gas, the particles of which can move about amongst each other.

There is a third method—radiation—by which heat can be carried from place to place, and this is quite different from either of the other two. If you stand in front of a fire the air between you and the fire may be quite cold, and yet you may feel that a great deal of heat is coming to you from the fire. Again, in a bright day in winter the air may be at a temperature below freezing-point, and yet the rays of the sun seem to be inconveniently hot. In these cases the heat has travelled through the air without making it hot, whereas, in either conduction or convection, the substance through which the heat is carried must itself be heated.

EXPERIMENT 13

Radiation.

Take one of the iron wires used in your experiments in conduction, and make one end of it white-hot in your Bunsen flame, take it out of the flame, and hold your hand about 10 cm. above it. Then heat it up again, and now hold your hand at the same distance from it, but on the same level. In which position does the hand receive most heat from the wire?

How was the heat carried from the wire to your hand in the first case? How in the second case?

Thus you see that a hot body exposed to the air gives out heat both by convection and by radiation.

* EXPERIMENT 14

Rate of cooling—Newton's Law of cooling.

For many experiments we require to know the rate at which a hot body cools by radiation. This rate is greater the greater the difference in temperature between the body which is giving out heat and the surrounding bodies which are receiving it. Newton formulated a law which he considered to be followed by cooling bodies, namely, "**The rate at which a body cools is directly proportional to the difference in temperature between it and its surroundings.**"

To test the truth of this law, take a metal cylindrical vessel about 10 cm. deep, and 6 or 8 cm. wide. Place it in a large beaker of water so as to float upright, with a few centimetres above the edge of the beaker. To do this it will be necessary to pour shot into the vessel to act as ballast.

Take a block of wood large enough to cover the beaker, and with a hole bored through it. Fit your thermometer so as to pass through a cork placed in this hole, and project about 6 or 8 cm. Take the temperature of the water in

the beaker, then, fitting the thermometer in the block of wood, heat the bulb of the thermometer to a temperature about 80° C. or 90° C. by holding it in the stream of hot air rising from your Bunsen burner, taking care that the wood is not heated at the same time. Then quickly place the block of wood on the top of the metal vessel and the beaker, as in Fig. 43, and note the temperature of the thermometer every half-minute until it falls to within about ten degrees of the temperature of the water in the beaker. The best way to do this is for one observer to take a watch with seconds hand and note-book, and call out to the other (who must keep his attention fixed on the thermometer) when he is to take a reading. In doing this, a good plan is to begin counting every second for 5 seconds before the time at which the observation is to be made, thus "5," "4," "3," "2," "1," "read."

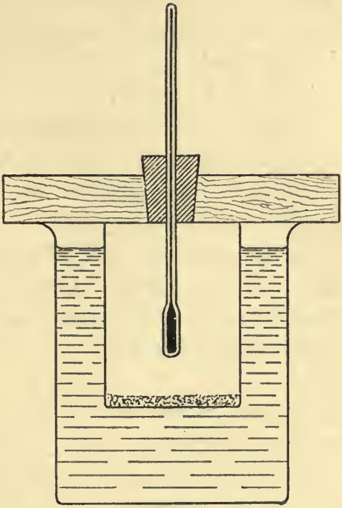

Fig. 43.

Write down your results in tabular form thus:—

Temperature of water in beaker and therefore of vessel = 17.3° C.

Time in Half-Minutes.	Temperature.
0	78.5
1	66.0
2	56.5
3	49.3
4	43.4
5	39.0
6	35.3
etc.	etc.

Having done this, take a piece of squared paper, and draw a curve showing the temperature observed every half-minute, by making abscissæ represent the times and ordinates to represent temperatures. A convenient scale will be obtained by taking each division to represent half minutes and degrees.

Now, just as we measure rate of walking by the number of miles walked over per hour, so we may measure rate of cooling by the number of degrees through which the temperature falls per minute.

Write down the rate of cooling for each minute during which the experiment lasted, and the difference in temperature between thermometer and enclosure at the *middle* of each minute, thus :—

	Fall in 1 Minute.	Difference in Temperature between Thermometer and Enclosure.
1st minute . .	22.0	48.7
2nd minute . .	13.1	32.0
3rd minute . .	8.1	21.7
4th minute . .	etc.	etc.

Using the test for proportionality, see p. xvi, find out whether Newton's Law is true, viz., whether the fall in temperature in 1 minute is proportional to the difference in temperature between the thermometer and enclosure.

Why do we note the difference in temperature between thermometer and enclosure at the *middle* of each minute and not at beginning or end?

CHAPTER III

CHANGE OF STATE

Experiment 15

Melting of ice.

Place some pieces of ice, each about 1 c.c. in volume, in a wide test-tube along with your thermometer, and note the temperature of the ice.

Then place this test-tube in a wide beaker containing water at about 30° C., and keep the ice in the test-tube well stirred with your thermometer. Note and record the reading of your thermometer every half-minute until about half the ice is melted. Take the test-tube out of the beaker and stir vigorously with the thermometer for about a minute, and again take the temperature of the ice and water.

Has any heat gone into the contents of the test-tube during this experiment? If so, where did it come from? Has the heat which has gone into the contents of the test-tube raised their temperature?

From this experiment state whether the temperature of ice at 0° C. is raised when heat goes into it. If the temperature does not rise, what is the effect of the heat?

The mark 0° C. on your thermometer is obtained by noting the position of the mercury in the stem when the thermometer is placed in melting ice. This temperature is sometimes called "freezing-point."

EXPERIMENT 16

Test the correctness of the scale of your thermometer as regards its freezing-point.

Place your thermometer in a funnel containing small pieces of clean ice, as in Fig. 44.

It is well to run some clean cold water from the tap over the ice before beginning this experiment. The reason for this will be seen from next experiment.

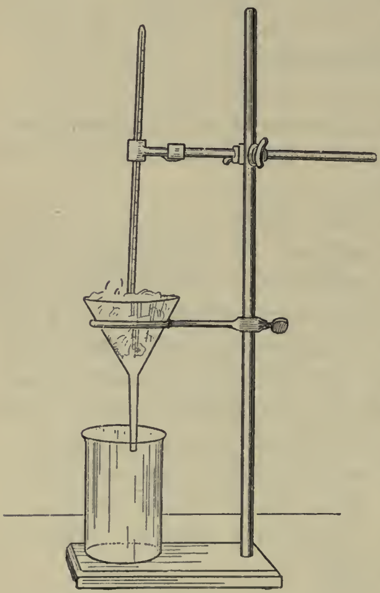

Fig. 44.

Leave it there for five minutes, and for five minutes more note the temperature every minute. If it is not 0° C. your thermometer is incorrectly graduated, and you must correct all subsequent readings of temperature accordingly.

Suppose the mercury stands at 0.7° C. then the 0° C. mark is too low, and you must subtract 0.7° C. from every reading of your thermometer to get the correct temperature. Since this amount has to be subtracted, the error of the thermometer at freezing-point is said to be - 0.7° C. If the mercury had stood at 0.7° C. below 0° C. the error would have been + 0.7° C., because 0.7° C. would have to

be added to the reading of the thermometer to get the true temperature.

What is the advantage of placing the ice in a funnel rather than in a test-tube or beaker?

Experiment 17

To make a freezing mixture.

Place in a small beaker some small pieces of ice, such as have been used in previous experiments, and sprinkle some common salt on the ice. Stir well with a thermometer and note the temperature.

You will notice many things about this experiment, such as the formation of hoar-frost on the beaker: write down an account of everything you notice. You will, later on, find an explanation of all.

Instead of putting salt on the ice, a more convenient freezing mixture for many purposes is obtained by pouring strong hydrochloric acid on it. The advantage of this is that as it remains liquid the mixture can be kept stirred easily without the risk of breaking any vessel which it may be desirable to cool down by means of the mixture.

Why is it desirable to wash the ice in last experiment with clean cold water?

Experiment 18

To find the melting or freezing-point of a substance.

We have seen, in Experiment 15, that while ice is melting its temperature does not rise although heat is being supplied to it. The temperature at which this takes place is called the melting-point of ice or freezing-point of water. If, instead of giving heat to ice at 0° C., we take heat away from water at 0° C., the temperature of the water

does not fall, but some of the water turns to ice; and, in fact, so long as the substance is partly in the liquid and partly in the solid state, its temperature does not alter whether heat be given to or taken from it. *The temperature at which a substance remains when it is changing from solid to liquid, or from liquid to solid, is called the* **melting-point** *or* **freezing-point** *of the substance.*

Into a small test-tube pour a small quantity of crystallised carbolic acid (absolute phenol), rather more than enough to cover the bulb of the thermometer when it is melted. Place the thermometer in the test-tube, and heat it with a small flame till the phenol is melted—it should not be heated to a higher temperature than 50° or 60° C. When it is all melted remove the burner and fix the test-tube in the retort-stand clamp, leaving the open end of the test-tube in the clamp. Taking a watch with a second hand, read the thermometer every half-minute until the temperature falls to about 33° C., noting the temperature in your book, just as in Experiment 14. This is best done by two observers, one keeping the watch while the other observes the thermometer.

Draw a curve having for ordinates the temperature of the substance and for abscissæ the time—each division on the horizontal axis representing one-half minute, and each division on the vertical axis representing 1° C.

What do you notice about this curve? At what temperature does the thermometer remain steady, and what is the melting-point of phenol?

Note 1.—**Overcooling.**—If the test-tube and its contents are kept very still, it is probable that the substance will at first cool to a temperature below its melting-point without solidifying. This phenomenon is called "overcooling" or "surfusion." As soon, however, as solidification begins the temperature rises to the melting-point, and remains steadily there until the whole has become solid.

For this reason it is desirable when finding the melting-point of a substance by this method to keep the liquid constantly stirred until solidification takes place.

Note 2.—**Substances with no definite melting-point.**—A large number of substances have no melting-point in the sense described above, *i.e.* they do not turn from liquid to solid at once, but go through an intermediate stage of plasticity or pastiness, and the temperature does not remain constant at any time, but falls very slowly. Such substances, therefore, cannot be said to have a definite melting-point. Would you expect iron, glass, sealing-wax, to have a definite melting-point?

Experiment 19

Solidification of paraffin wax, and change of volume on solidification.

Melt some paraffin wax in a test-tube, as in last experiment, taking care not to heat it enough to discolour it or make it smoke. Note its temperature every half-minute, as in last experiment, as it falls from 65° C. to 45° C., and draw its "curve of cooling" on the same sheet as that which you used for phenol.

Note the difference between the two substances as regards their cooling and solidifying.

Note the surface of the wax before and after it has solidified, and state whether solid wax or liquid wax has the greater volume.

Would you expect solid wax to float or to sink in liquid wax? Explain clearly the reason for your answer.

Does ice float or sink in water? Answer this from your own experience without trying it by experiment.

Does water, then, take up more or less room when solid than it does when liquid?

* Experiment 20

Direct experiment to find whether water expands or contracts on solidifying.

Place as much water in a narrow test-tube as will fill about half of it; then take a perforated india-rubber stopper which will fit the test-tube, and fit into the stopper a piece of quill tubing about 20 cm. long. Fill up the test-tube with paraffin oil, and insert the stopper and tube, taking care that no air is imprisoned. The oil will rise up the tube and remain steady as long as the temperature remains the same.

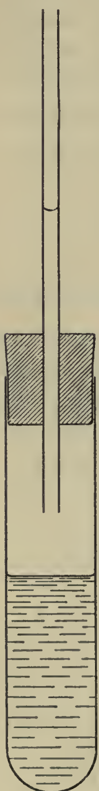

Fig. 45.

Place the test-tube in a freezing mixture, and notice the effect on the oil in the tube till the water has become nearly all frozen. Write an account of what you have observed, and state what the experiment proves.

Explain the bursting of water-pipes in frosty weather.

What happens in winter when the water which fills the cracks and crevices in a piece of rock becomes frozen?

Experiment 21

Boiling point.

Take a flask with a cork fitting the neck of the flask, and pass through two holes in the cork your thermometer and a piece of glass-tubing, bent as in Fig. 46.

Pour some water into the flask, and put in the cork

so that the bulb of the thermometer is in the water. Heat the flask by your Bunsen burner and notice the thermometer.

You will observe that the temperature of the water rises steadily for some time and then stops rising.

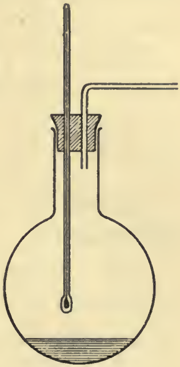

Fig. 46.

What is the temperature at which the thermometer stops rising? What do you notice about the water?

Raise the thermometer till the bulb is just above the surface of the water, and note the temperature.

Place about 50 grammes of common salt in the water, and, after it has been dissolved, take the temperature of the boiling water and then of the steam.

In doing this the thermometer bulb should be well cleaned after being in the salt water and before being placed in the steam. If any salt be allowed to remain on the bulb it will affect the result.

What is the effect of the salt on the temperature of the water while it is boiling? What is the effect of the salt on the temperature of the steam which comes from the boiling water?

Experiment 22

Effect of pressure on boiling-point.

Using the same apparatus as in last experiment, fix to the end of the escape-tube a short piece of indiarubber tubing capable of being closed by a spring clip. Place the thermometer so that its bulb is just above the surface of the water, and, while the water is boiling freely, note its reading when steady, then close the escape-tube by the clip and notice the thermometer. You will find that it rises.

As soon as the thermometer has risen 2° above its reading

while the tube was open, allow the imprisoned steam to escape by opening the clip. You will notice that it goes out with a rush, showing that it has been under pressure.

What, then, is the effect upon the temperature of the steam from boiling water of increasing the pressure on it?

Either find out for yourself, or ask your teacher to tell you, the height of the barometer, and note it.

Experiment 23

Testing the accuracy of the boiling-point on your thermometer.

The preceding experiments have shown that the temperature of the steam from boiling water depends on the pressure but does not depend on the state of purity of the water. This fact is used in graduating thermometers, just as the constancy of the melting-point of pure ice is. If the thermometer is correctly graduated, it ought to show a temperature of 100° C. when placed in the steam from water boiling in a vessel open to the air when the barometer stands at 76 cm.

If the barometer is not at 76 cm., the true temperature of the steam can be obtained from the following table :—

Height of Barometer.	Temperature.	Height of Barometer.	Temperature.
74.0 cm.	99.25° C.	75.6 cm.	99.85° C.
74.2 ,,	99.33° C.	75.8 ,,	99.93° C.
74.4 ,,	99.41° C.	76.0 ,,	100.00° C.
74.6 ,,	99.48° C.	76.2 ,,	100.07° C.
74.8 ,,	99.56° C.	76.4 ,,	100.14° C.
5.0 ,,	99.63° C.	76.6 ,,	100.22° C.
75.2 ,,	99.70° C.	76.8 ,,	100.29° C.
75.4 ,,	99.77° C.	77.0 ,,	100.37° C.

Find, from this table, the temperature of the steam from boiling water corresponding to the height of the barometer as observed in last experiment, and thence calculate the

error of your thermometer at boiling-point; remembering, as in Experiment 16, that if the correction has to be added to the reading of your thermometer it has the *plus* sign, and if it has to be subtracted it has the *minus* sign.

Experiment 24

To find the boiling-point of any liquid.

Take a flask with a long neck, and a side tube coming out of the neck, as in the diagram. One of the flasks generally used by chemists for fractional distillation suits very well. Fit a cork to the mouth of the flask, bore a hole in this cork to fit your thermometer, and place the thermometer in the cork so that the bulb should be just above the surface of the liquid whose boiling-point is required, when the liquid is poured into the flask. The flask should then be placed in a sand bath, *i.e.* a metal tray filled with sand, and the whole heated by means of your Bunsen burner until it boils; note the temperature indicated by the thermometer, and when this has remained constant for two or three minutes it may be read and taken as the boiling-point of the liquid.

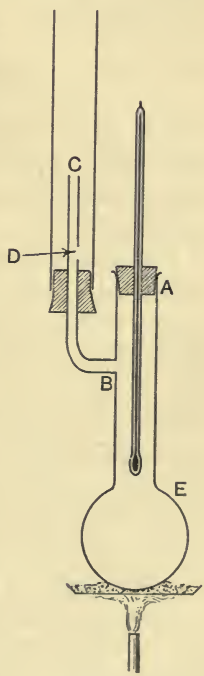

Fig. 47.

In order that the boiling may take place quietly and not by bumping, a small piece of hard carbon, such as is used for arc lamps, should be placed in the liquid. This forms a nucleus for the vapour to form on, and makes the ebullition more uniform.

In order to prevent the vapour escaping into the room, and thus using up an unnecessarily large quantity of liquid, and at the same time affecting the atmosphere of the room, it is convenient to attach to the vertical discharge tube BC a wider piece of glass tubing, about 50 cm. long or more, by means of a cork or sleeve of indiarubber tubing. There must then be made in the side of the inner tube BC a hole as at D, in order that the liquid condensed in the wide tube should be able to run back into the flask without interfering with the escape of the steam at C.

In this way we can find the boiling-point of liquids which boil at temperatures up to about 180° C.

For liquids of higher boiling-points, and, in fact, for all liquids, it is an advantage to surround the neck AE of the flask with a cover of asbestos cardboard. This hinders the loss of heat from the thermometer by radiation to surrounding objects.

For liquids which when hot act on indiarubber it is desirable to pour a little mercury into the wide tube so as to rest on the indiarubber, and thus protect it from the action of the liquid.

CHAPTER IV

MEASUREMENT OF QUANTITY OF HEAT, OR CALORIMETRY

Quantity of Heat

In the preceding experiments we have spoken of heat going from one body into another so that the temperature of the one body falls and that of the other rises; of heat travelling or being conducted along a wire; of heat going into ice and causing it to melt. We now proceed to consider how we can measure the quantity of heat transferred from one body to another.

Suppose we take two bodies of exactly the same material and the same mass, and at the same temperature, and raise the temperature of each to the same (higher) temperature, then we must admit that the same quantity of heat must have been given to each. Therefore the two together have received twice as much heat as either by itself. From this it follows that to raise 2 gm. of any substance through any number of degrees requires twice as much heat as to raise 1 gm. of that substance through the same range of temperature. Thus also to raise 20 gm. of water from 0° C. to 1° C. we must use twenty times as much heat as to raise 1 gm. of water from 0° C. to 1° C.

The *unit of heat quantity* which we generally use is *that quantity of heat which is required to raise the temperature of*

1 gm. of water from 0° C. to 1° C., and it is generally called a **Calorie.**

Write down in your note-book the answers to the following questions :—

1. How much heat is required to raise 35 gm. of water from 0° C. to 1° C. ?

2. How much heat is given out by 70.6 gm. of water falling from 1° C. to 0° C. ?

3. How much water will be heated from 0° C. to 1° C. by 49 calories ?

It does not follow from anything which we have so far learnt that twice as much heat is required to raise the temperature of a body from 0° C. to 2° C. as to raise the temperature of the same body from 0° C. to 1° C. In order to find out whether this is the case we must try it by experiment.

If we mix together two equal quantities of water at different temperatures, say 10° C. and 30° C., and find that the temperature of the mixture is 20° C., then we may reason as follows :—The heat which has gone out of the hot water as it cooled from 30° C. to 20° C. has gone into the same mass of cold water and raised it from 10° C. to 20° C. Hence a given mass of water falling from 30° C. to 20° C. gives out enough heat just to raise the same mass of water from 10° C. to 20° C. Hence the same amount of heat is needed to raise a given mass of water from 10° C. to 20° C., as is required to raise the same mass of water from 20° C. to 30° C.

If the temperature of the mixture were below 20° C., what answer would you give to the question whether the same amount of heat is needed to raise a given quantity of water from 10° C. to 20° C. as from 20° C. to 30° C. ? What if the temperature of the mixture were above 20° C. ?

EXPERIMENT 25

To find whether the quantity of heat required to raise the temperature of a given mass of water through 1° C. is the same at all temperatures.

Take two large beakers of nearly equal size (about 600 c.c. capacity), and pour into one 250 gm. of cold water, and into the other the same mass of warm water. The temperature of the warm water should not be higher than 30° C. or 40° C. (See that the beaker is counterpoised before you weigh the water.)

Take the temperature first of the cold water and then of the hot, and quickly pour the hot water into the cold, stir well, and note the temperature of the mixture.

Through how many degrees has the temperature of the hot water fallen?

Through how many degrees has the temperature of the cold water risen?

Now, in the argument given above, we assumed that the two quantities of water were mixed in such a way that all the heat which went out of the hot water went into the cold. But in this experiment we are not justified in saying this, because not only has the temperature of the cold water been raised but that of the beaker which contains it as well. Therefore only part of the heat which has come out of the hot water has gone into the cold water.

To get over this difficulty repeat the experiment, only, instead of pouring the hot water into the cold, pour the cold into the hot. Note the number of degrees through which the hot water has fallen and the cold water has risen.

In this case has all the heat which came out of the hot water gone into the cold?

Has the cold water received any more heat than that which came from the hot water?

Would you therefore expect the rise in temperature of the cold water to be equal to the fall in temperature of the hot?

State, as the result of these two experiments, whether you consider that we are justified in saying that the same quantity of heat is needed to raise the temperature of a given mass of water through 1° C. at all temperatures.

We may now say that, so far as our experiments go, 1 calorie is needed to raise the temperature of 1 gm. of water through 1° C. at any temperature, *i.e.* not only from 0° C. to 1° C. but from 18° C. to 19° C., from 49° C. to 50° C., and so on.

Answer the following questions :—

1. In the first experiment how much heat went into the cold water?

2. How much heat came out of the hot water?

3. How much heat was lost to the glass and in other ways?

In the second experiment—

4. How much heat went into the cold water?

5. How much heat left the hot water?

6. How much heat came out of the glass after deducting losses by cooling to the air?

Examples

1. How much heat is needed to raise 640 gms. of water from 12° C. to 17.8° C.?

2. How much heat is given out by 140.6 gms. of water in cooling from 60.7° C. to 49.8° C.?

3. How much heat is needed to raise 314 gms. of water from freezing-point to boiling-point?

4. Through how many degrees will 480 gms. of water be raised by 1680 calories?

5. A block of hot iron is dropped into a vessel containing 230 gms. of water at 18° C. and raises the temperature of the water to 25.6° C. How much heat was given out by the block?

SPECIFIC HEAT

A very few experiments will show that different substances require very different quantities of heat to raise the temperature of a given mass through a given number of degrees. This fact is expressed by saying that they have different "*specific heats.*"

The **specific heat** *of any substance is the ratio of the quantity of heat required to raise any quantity of that substance through one degree centigrade to the quantity of heat required to raise the same mass of water from* 0° *C. to* 1° *C.* Now, we have seen that 1 calorie is the quantity of heat required to raise 1 gm. of water from 0° C. to 1° C. Hence we see that *the specific heat of any substance is simply the number of calories required to raise the temperature of* 1 *gm. of that substance through* 1° *C.*

Also, since the same quantity of heat is given out by a body in falling through any range of temperature as is taken in by the same body in rising through the same range of temperature, it follows that the specific heat of a substance may be expressed by *the number of calories that* 1 *gm. of that substance gives out in falling* 1° *C.*

EXPERIMENT 26

To find the specific heat of copper.

Weigh out about 30 gm. of short pieces of copper wire and place them in a test-tube. Place this test-tube, with the copper and a thermometer inside it, in a beaker of water and heat this water till it boils, and leave it boiling for some time. (It is well to close the mouth of the test-tube with a plug of cotton wool while it is in the boiling water.)

While this is going on, take a calorimeter (a cylindrical vessel of thin sheet copper or brass about 4 cm. diameter

and 7 cm. high) and counterpoise it in one pan of the balance. Then pour into the calorimeter about 40 gm. of cold water, weighing the water accurately. In practice it will simplify your calculation somewhat if you take exactly 40 gm.

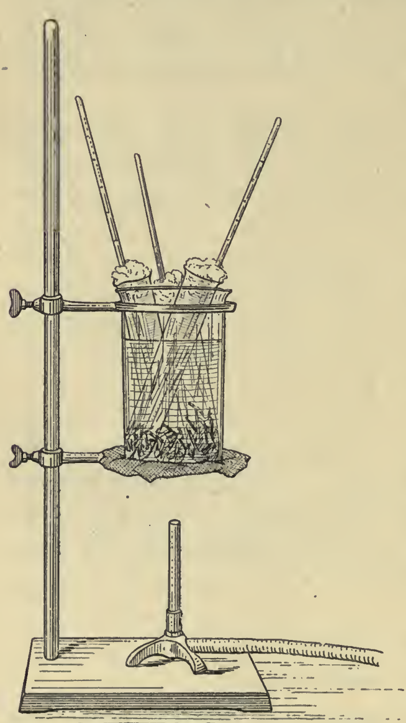

Fig. 48.

Place the calorimeter on a piece of cork at some distance from your Bunsen burner, until the thermometer in the copper has ceased to rise. Note the temperature of the copper when this is the case, and remove the thermometer from the test-tube, cool it in cold water from the tap and wipe it. Then place it in the water which you weighed into the calorimeter, and note the temperature of the water.

Leaving the thermometer in the calorimeter, quickly take the test-tube out of the beaker of boiling water and pour the copper into the calorimeter as rapidly as possible. Stir the copper in the water by means of your thermometer for about half a minute, and then note the temperature of the mixture.

Record your results as follows :—

Mass of copper	=	gm.
Temperature of copper	=	°C.
Mass of water	=	gm.
Temperature of water	=	°C.
Temperature of mixture	=	°C.

What is the rise in temperature of the water?

How much heat, therefore, has the water received?

Where did this heat come from?

Assuming that all the heat which went out of the copper in cooling down to the temperature of the mixture went to heat the water, how much heat has been given out by the copper?

How many degrees has the temperature of the copper fallen?

How much heat will be given out by the copper in falling 1° C.?

How much heat will be given out by 1 gm. of copper falling 1° C.?

What is the specific heat of copper?

Is the assumption that all the heat which left the copper has gone into the water really justified? If not, where has any of this heat gone to? (See Experiment 25.)

Experiment 27

Water equivalent of calorimeter.

The calorimeter in last experiment had its temperature raised along with the water which it contained, thus the heat given out by the copper in cooling not only raised the temperature of the 40 gm. of cold water but that of the calorimeter also. Hence this source of error can be avoided if we suppose that instead of having taken 40 gm. of cold water we had taken 40 gm. + a quantity of water

which requires the same quantity of heat to raise its temperature as the calorimeter does. This quantity is called the *water equivalent* of the calorimeter, thus :—
The **water equivalent** *of any body is the mass of water which requires the same quantity of heat to raise its temperature through any number of degrees as the body does.*

If we know the specific heat of the substance of which the calorimeter is made, we can easily find the water equivalent by weighing the calorimeter and multiplying the result by the specific heat. The specific heat of brass may be taken as .094; calculate the water equivalent of your calorimeter.

Experiment 28

Second experiment to find the water equivalent of the calorimeter.

Thoroughly dry your calorimeter, counterpoise it with shot in one pan of your balance, and then remove it from the balance and place it on a piece of cork at some distance from your Bunsen burner. Place your thermometer inside the calorimeter, and leave it there for at least five minutes, so that the thermometer, the calorimeter, and the air may all have the same temperature.

Meanwhile heat some water in a beaker over your Bunsen burner till it is about 30° C. Remove the beaker from the burner and place it on the table. After the five minutes has elapsed note the temperature of the thermometer (and therefore of the calorimeter). Place your thermometer in the water in the beaker, and if it is above 30° C. put some cold water into it till the temperature is somewhere between 25° C. and 30° C. Note this temperature, and then pour the water into the calorimeter till it is about half full. Stir the water in the calorimeter with

your thermometer, and after about a minute note the temperature again. Take out the thermometer, replace the calorimeter in the balance pan, and so weigh the water which you have poured in. Write your results thus :—

Temperature of calorimeter	=	°C.
Temperature of water before pouring in	=	°C.
Temperature of water after pouring in	=	°C.
Mass of water poured in	=	gm.

Knowing the mass of water and the number of degrees through which its temperature has fallen, find the quantity of heat given out by the water. What has this heat done?

How much heat has been required to raise the temperature of the calorimeter?

How many degrees has this temperature been raised?

How much heat, therefore, is needed to raise the temperature of the calorimeter 1° C.?

How much water would be raised 1° C. by this quantity of heat?

What then is the water equivalent of the calorimeter?

The reason for not having the water which is poured into the calorimeter too hot, is that if it is very hot its temperature falls quickly, owing to the loss of heat to the surrounding air. Thus the heat lost by the water would not nearly all go into the calorimeter, and the water equivalent thus found would be too large.

Experiment 29

Third experiment to find the water equivalent of the calorimeter.

Instead of pouring the warm water into the empty calorimeter, pour it into some cold water already in the

calorimeter, having previously weighed this cold water. Write your results as follows :—

Mass of water in calorimeter to start with	=	gm.
Temperature of this water	=	°C.
Mass of warm water poured in	=	gm.
Temperature of this water before pouring in	=	°C.
Temperature of mixture	=	°C.

Find the quantity of heat given out by the hot water and that taken in by the cold. The difference will be the quantity taken in by the calorimeter. Thus knowing how many degrees the calorimeter has had its temperature raised, you can calculate the number of calories required to raise the temperature of the calorimeter 1° C., and therefore the water equivalent of the calorimeter.

Which of these three methods do you consider the best, and why?

Experiment 30

To find the water equivalent of your thermometer.

Place about 30 gm. of cold water in your calorimeter and place the calorimeter on a cork. Heat some water to near boiling-point.

Note the temperature of the cold water, and then heat the thermometer by placing it in the hot water. Taking the thermometer out of the hot water, wipe it rapidly with a cloth and hold it above the calorimeter. As soon as the thermometer falls to about 70° C. or 80° C., place it rapidly in the cold water and stir for a minute or two, and then note the temperature of the water, which will be found to be somewhat higher than before.

Calculate the quantity of heat that the calorimeter and the water in it have received. Since this heat has come from the thermometer, you know the number of calories

given out by the thermometer in cooling through so many degrees. Hence you can calculate the quantity of heat given out by the thermometer in falling one degree, and therefore the required water equivalent.

A very accurate result can be obtained with very little trouble, by repeating the experiment several times, using the same water in the calorimeter each time. Thus, the temperature of the water after being heated by the thermometer in the first experiment is the temperature of the cold water in the second experiment, and so on. These experiments can be easily performed in a few minutes, and the gain in accuracy is very considerable.

Experiment 31

Correction of specific heat of copper.

Having found the water equivalent of calorimeter and thermometer, you are now able to allow for the quantity of heat absorbed by them in Experiment 26. For the quantity of heat given out by the copper was not that taken in by the water, but that taken in by an amount of water equal to the quantity actually weighed + the water equivalents of calorimeter and thermometer.

Calculate the result of Experiment 26, allowing for the heat absorbed by calorimeter and thermometer.

Suggestions for other Experiments

1. In the same way as here described it is easy to find the specific heat of such substances as lead, iron, zinc, glass (in very small pieces), sand, etc.

2. In a similar way we can find the temperature of an enclosure such as an oven by heating in it a weighed block of a metal whose specific heat is known, and then dropping the metal into a weighed quantity of cold water in a calorimeter. As before we can find the quantity of heat given out by the metal, and thence knowing its mass and specific heat can calculate its fall in temperature.

Specific heat of a liquid which cannot be mixed with water.—Several liquids, such as sulphuric acid and alcohol, when mixed with water produce a rise in temperature, and therefore the specific heat of such a substance could not be found by the ordinary method of mixtures. Some other liquids, such as turpentine, do not readily mix with water, and therefore a long time must elapse, even with vigorous stirring, before the temperature of the whole of the mixture becomes uniform.

Hence before trying to find the specific heat of any substance by the method just described, care must be taken to find out whether the substance is in any way acted upon by water. This can generally be tested by mixing quantities of the given substance and of water at the same temperature, and finding whether any rise or fall in temperature takes place.

In all such cases the specific heat can be found by the following method, it being noted that the metal taken must be one which does not have any chemical action on the liquid.

Experiment 32

To find the specific heat of alcohol by mixing with copper.

Weigh out about 20 gm. of short pieces of copper wire, place them in a test-tube with your thermometer, and heat in a beaker of boiling water as in Experiment 26. Weigh or counterpoise your calorimeter when empty, and pour into it enough alcohol to fill it about three-quarters full; weigh the amount of alcohol you have thus taken.

When the temperature of the copper has risen so high that it becomes constant, note it and then take out the thermometer, and with it carefully note the temperature

of the alcohol. Then pour the copper into the alcohol, stir, and note the temperature of the mixture.

Then since the specific heat of copper is .095, 1 gm. of copper falling 1° C. gives out .095 calories. Write down the quantity of heat which has gone out of the copper. This heat has gone to heat the alcohol and the calorimeter. Knowing the rise in temperature of the calorimeter and its water equivalent, you can find the quantity of heat which it has received.

Hence the quantity of heat given out by the copper *minus* the quantity taken up by the calorimeter and thermometer must be the quantity which has gone into the alcohol.

How much heat then has gone into the alcohol?

Hence we know that ... gms. of alcohol rising through ...° C. take in ... calories, and thus we can calculate the number of calories required to raise 1 gm. of alcohol through 1° C., *i.e.* the specific heat of alcohol.

The following is an example of such an experiment as that just described:—

Mass of copper	= 20.00 gm.
Mass of alcohol	= 36.20 gm.
Water equivalent of calorimeter and thermometer	= 4.8 gm.
Initial temperature of alcohol	= 18.3° C.
Initial temperature of copper	= 99.3° C.
Temperature of mixture	= 23.5° C.

20 gm. of copper falling from 99.3° C. to 23.5° C.,
i.e. through 75.8° C. give out $20 \times .095 \times 75.8 = 144.02$ calories.

Calorimeter and thermometer rising from 18.3° C. to 23.5° C.,
i.e. through 5.2° C. take in $4.8 \times 5.2 = 24.96$ calories.

Hence the alcohol has taken in $144.02 - 24.96 = 119.06$ calories,
i.e. 36.2 gm. of alcohol rising 5.2° C. take in 119.06 calories,

$\therefore$ 1 gm. of alcohol rising 1° C. takes in $\dfrac{119.06}{36.2 \times 5.2}$ calories
$= .63$ calories

$\therefore$ Specific heat of alcohol $= .63$.

*Experiment 33

Second experiment to find the specific heat of alcohol.

The accuracy of last experiment depends on the accuracy of the value which we adopt for the specific heat of copper. The following method avoids this difficulty.

Weigh out three equal quantities of copper, each weighing 20 gm., and place them in test-tubes, heating them in boiling water as before.

Pour into your calorimeter a quantity of water weighing about two-thirds as much as the alcohol in last experiment. Adjust the temperature of this water (by surrounding the calorimeter with cold water from the tap, if it is too high, or by warming it by holding it in the hand, if it is too low) till it is the same as that of the alcohol in last experiment; and, when the copper has reached the same temperature as it had in last experiment, pour the contents of one of the test-tubes into the calorimeter, stirring and noting the temperature of the mixture. If this temperature is the same as that of the mixture of alcohol and copper, then we can say that the quantity of alcohol which you took is thermally equivalent to the quantity of water in this experiment.

If the temperature of the mixture in this experiment is higher than in last experiment, empty the calorimeter and pour into it a larger quantity (about 2 or 3 gm. more) of water, and repeat the experiment just described. If the temperature of the mixture is still too high, repeat the experiment with a still greater quantity of water. (Similarly, if the temperature of the mixture had been lower in this than in last experiment, you would have taken a smaller quantity of water in repeating the measurement.)

In this way we can find two quantities of water not

differing much in mass, one of which is too small and the other too large to be thermally equivalent to the quantity of alcohol in last experiment, and thus we can calculate the mass of water, which would be exactly equivalent to the given mass of alcohol. This will be made clearer by an example which will also show how the observations should be written down :—

20 gm. of copper falling		from 100° C. raise
32 gm. of alcohol	,,	from 18° C. to 24.3° C.
22 gm. of water	,,	from 18° C. to 24.5° C.
24 gm. of water	,,	from 18° C. to 24.0° C.

Hence, the thermal equivalent of 32 gm. of alcohol lies between 22 and 24 gm. of water.

Now, adding 2 gm. of water lowers the temperature of the mixture from 24.5° C. to 24° C., *i.e.* .5° C. How much water must be added to lower the temperature from 24.5° C. to 24.3° C., *i.e.* .2° C.? The answer is $\frac{\cdot 2}{\cdot 5} \times 2$ gm. = .8 gm.

Hence, if we had added .8 gm. of water, the temperature would have been raised from 18° C. to 24.3° C., *i.e.* through the same number of degrees as the alcohol was. Hence 22.8 gm. of water are thermally equivalent to 32 gm. of alcohol.

Having found in this way how many grammes of water are equivalent to the quantity of alcohol which we used, we can proceed as follows :—

32 gm. of alcohol are thermally equivalent to 22.8 gm. of water.

∴ 1 gm. of alcohol is equivalent to $\frac{22.8}{32} = .71$ gm. of water.

Therefore the specific heat of alcohol is .71.

It has to be noted that in this experiment it is not necessary to take account of the water equivalents of calorimeter and thermometer, or of any loss of heat from

the calorimeter to the air, etc. For all these are exactly the same in each case, so that we are justified in saying that the quantity of water is thermally equivalent to the given quantity of alcohol, so long as the calorimeter and thermometer which we use are the same throughout the experiment.

Why do we take a mass of water about two-thirds of the mass of alcohol?

* Experiment 34

To find the specific heat of a liquid by method of cooling.

Take a calorimeter, whose outside surface is blackened, and place it inside another cylindrical vessel supported on pieces of cork as in the diagram, so that as little heat as possible may pass from the calorimeter to the outer vessel by conduction.

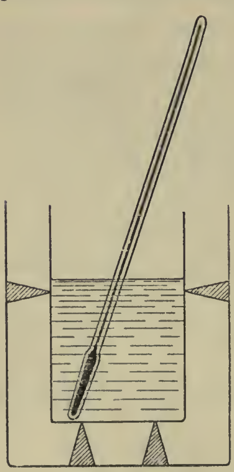

Fig. 49.

Place the whole in a basin containing cold water, so that the water rises to within 2 cm. of the top of the outer vessel. It will probably be necessary to weight this vessel down with shot in order to prevent it floating. Note the temperature of the water bath, and pour in enough of the liquid (turpentine will be found suitable) at a temperature of 50° C. or 60° C. to fill the calorimeter about two-thirds full.

While one stirs the liquid with the thermometer and notes the temperature, let the other keep his eyes fixed on a watch with seconds hand,

and note the exact time at which the thermometer is at every even degree of temperature. The first, keeping his eye on the thermometer, should say, *e.g.* "50," "48," "46," etc., as these temperatures are reached, while the other notes the number of minutes and seconds indicated by the watch at the time each number is called out. Then draw up a table as follows:—

Temperature.	Time.
52° C.	3 hrs. 46 min. 5 sec.
50° C.	,, 47 ,, 5 ,,
48° C.	,, 48 ,, 14 ,,
46° C.	,, 49 ,, 34 ,,
44° C.	,, 50 ,, 56 ,,
etc.	etc.

Carry this on from about 50° C. to 40° C. Then take out the calorimeter and weigh it with its contents; empty out the liquid, dry the calorimeter, and weigh it empty. Thus we can find the mass of the liquid used.

Then pour into the calorimeter the same volume (approximately) of water at about 60° C., and note as before the times at which it is at *the same temperatures as before.*

Then weigh the calorimeter and water, and thus find the mass of water.

Draw up a table like the following:—

	50-48.	48-46.	46-44.	44-42.	42-40.
Time (in seconds) taken by liquid in falling 2° C. = .	69	80	82	90	114
Time taken by water in falling 2° C. = ...	95	100	109	134	142

Work out to three places of decimals each of these ratios, thus—

$$\frac{69}{95} = .726. \qquad \frac{82}{109} = .752. \qquad \frac{114}{142} = .803.$$

$$\frac{80}{100} = .800. \qquad \frac{90}{134} = .672.$$

Find the average of these values; it is found to be in this case $= .751$.

Hence the time taken by the liquid to fall 2° C. is .751 of the time taken by the water in falling through *the same range of temperature.*

Hence we may say that since heat is being given out at the same rate in both cases, the heat given out by the liquid in falling 2° C. is .751 of that given out by the water.

But the mass of liquid was not equal to that of water. Suppose the mass of liquid to be 25.4 gm., and that of the water 30 gm., then the heat given out by 25.4 gm. of the liquid in falling 1° C. is .751 of that given out by 30 gm. of water falling 1° C.

Therefore the heat given out by 1 gm. of the liquid falling 1° C. is $.751 \times \frac{30}{25.4}$ of that given out by 1 gm. of water falling 1° C., that is, $.751 \times \frac{30}{25.4}$ calories.

Therefore the specific heat of the liquid is

$$.751 \times \frac{30}{25.4} = .887.$$

The reason for taking equal *volumes* and not equal *masses* of the liquid is that the conditions of the two while cooling should be as nearly identical as possible.

In this experiment we have taken no account of the water equivalents of calorimeter or thermometer. What effect do you consider this omission will have on the result?

Latent heat.—In Experiments 15 and 18 it has been seen that so long as heat is supplied to ice at 0° C. no rise in temperature is produced; the heat is used up in melting the ice. As soon as all the ice is melted, any further supply of heat causes the temperature of the melted ice to rise. The heat which goes into a solid to melt it without making it warmer is said to become "latent" or hidden. It actually disappears as heat, but can be made to reappear again when the liquid turns back into the solid condition. *The quantity of heat required to convert* 1 *gm. of any solid into liquid without raising its temperature is called the* **Latent Heat of Fusion** *of that substance.*

In the same way, in Experiment 21, we have seen that heat supplied to boiling water does not raise its temperature. In this case again the heat becomes "latent," and *the quantity of heat required to convert* 1 *gm. of liquid into vapour without changing its temperature is called the* **Latent Heat of Vaporization** *of that liquid.*

Similarly, when vapour condenses into liquid it gives out this latent heat again.

Freezing mixtures.—We have seen that heat must be supplied to ice in order that the ice should melt, and that this heat produces no rise in temperature. If it were possible, therefore, to cause ice to melt without supplying heat to it from outside, the necessary amount of heat would have to be supplied by the ice itself. Hence the temperature of the ice and surrounding bodies would fall. This is the principle of freezing mixtures (Experiment 17). When the salt or hydrochloric acid is mixed with ice, the ice is caused to melt, and, unless heat is supplied to it, the "latent heat" required to melt the ice is taken from the ice itself, and from anything which is in contact with it. Thus the temperature of the mixture itself, and of bodies in contact with it, is lowered by the loss of this heat.

EXPERIMENT 35

To find the latent heat of fusion of ice.

Counterpoise a beaker of about 400 c.c. capacity, and pour into it 200 gm. of warm water at a temperature of about 40° C.

Stand the beaker on a piece of cork, and take a quantity of ice in small pieces.

Having noted the temperature of the water carefully, place in it a quantity of ice, taking care to dry the ice with a cloth as you place each piece in the water. Stir well with the thermometer till all the ice is melted, and note the temperature of the mixture of water and melted ice. The quantity of ice melted should be enough to bring the temperature down to about 8° C. or 10° C.

Then weigh the beaker and its contents, and thus find how many grammes of ice have been melted.

Write down your results as follows:—

Mass of water	=	gm.
Temperature of water before ice is put in	=	° C.
Temperature of water after ice is melted	=	° C.
Mass of ice melted	=	gm.

How much heat has the warm water given out in cooling?

Some of this heat has caused the ice to melt, and the rest has raised the temperature of the melted ice. What is the rise in temperature of this melted ice?

How much of the heat given out by the warm water has gone to raise the temperature of the melted ice?

How much heat, therefore, must have been used in causing the ice to melt without change of temperature?

How much ice was melted?

How much heat is needed to melt 1 gm. of ice without changing its temperature?

What then is the latent heat of fusion of ice?

Having calculated in this way the latent heat of fusion of ice, state what sources of error exist in the experiment as here described.

EXPERIMENT 36

To find the latent heat of vaporization of water (sometimes called the latent heat of steam).

Take a flask of about 500 c.c. capacity, fill it about half-full of water, and fit into it a cork through which passes a piece of glass tubing bent twice at right angles. (See Fig. 51.) The end of this tube passes through a cork in a wider tube, which is designed to act as a trap to catch any of the steam which has condensed in the tube above it. The bottom of this trap is formed by a cork through which passes another straight tube as in Fig. 50. This tube should have its lower end at such a height above the table that a second flask, as described below, can be rapidly placed so that this tube reaches to near the bottom of the flask.

Fig. 50.

Adjust the whole on the retort stand with Bunsen flame under the flask, as in Fig. 51. Then counterpoise a flask of 500 or 600 c.c. capacity and pour into it 300 or 400 gm. of cold water, adjusting it carefully with a pipette. Set it on a piece of cork.

As soon as steam comes freely from the end of the delivery tube bring up the flask of cold water, having carefully noted its temperature, and place it on its

piece of cork and wooden blocks, so that the end of the delivery tube reaches down to near the bottom of the cold water. The time at which this is done should be noted and recorded.

Fig. 51.

Allow the steam to pass into the cold water until the temperature rises to about 50° C., removing the condensing flask from the delivery tube after the expiry of a whole number of minutes from the time of bringing it up. When this has been done, the Bunsen flame may be removed.

Stir the water well with the thermometer, and note its temperature. Then note its temperature again one minute later. This will give us the rate at which the water is cooling.

Then weigh the water in the flask; the increase will be the mass of steam which has been condensed. Write down your results as follows:—

Mass of cold water	= 400 gm.
Temperature	= 12° C.
Time at which experiment began	= 10 hrs. 26 min.

Temperature of mixture	$=47°$ C.
Time at which experiment ended	$=10$ hrs. 32 min.
Fall of temperature in 1 minute	$=.5°$ C.
Mass of steam condensed	$=25.7$ gm.

When the steam comes in contact with the cold water it condenses into water at 100° C., giving up its latent heat, and then this hot water mixing with the cold water gives up more heat.

In this way the cold water is gradually heated. But at the same time that the cold water is receiving heat from the condensation of the steam, heat is continually escaping into the air from the condensing water, and the hotter this becomes the quicker does the heat leave it. (See Experiment 14—Newton's Law of Cooling.)

Now at the beginning of the experiment the temperature of the condensing water was the same as that of the air, or very nearly so. Therefore at the beginning there would be no loss of heat to the air.

At the end of the experiment we found the fall in temperature in 1 minute. Hence, since the rate of cooling of a body is proportional to the difference in temperature between the body and its surroundings, we can find the temperature which the condensing water would have had if no heat had been lost, by assuming the fall in temperature every minute throughout the experiment to be the average between the fall in 1 minute at the beginning and at the end of the experiment. Now at the beginning the fall was *nil.* Hence the average fall every minute is half the fall in 1 minute at the end of the experiment.

Thus, in the example we have taken, the average fall per minute is $=\frac{0+.5}{2}=.25°$C.

Hence, as the experiment lasted for 6 minutes, we conclude that had no cooling taken place the temperature would have been $6 \times .25$ or $1.5°$ C. higher than it really was.

Hence the temperature of the mixture, allowing for cooling, was $47. + 1.5 = 48.5°$ C.

Find in this way the corrected value of the temperature of the mixture in your experiment.

Then calculate the quantity of heat which has gone into the cold water. This heat has been given out partly by the steam in condensing to water at 100° C., and partly by this condensed water in cooling from 100° C. to the temperature of the mixture. How much heat has been given out in the latter of these two processes?

Knowing the total quantity of heat received by the cold water, and the quantity which has been given out by the condensed steam, we find the quantity which has been given out by the steam in condensing into water without change of temperature. How much is this?

How much heat would therefore be given out by 1 gm. of steam in condensing without change of temperature?

As the above reasoning may be too difficult for some, it is summarised below in the form of a specimen experiment worked out.

Taking the numbers given above, we see that 400 gm. of water rising from 12° C. to 48.5° C., *i.e.* through 36.5° C. take in $400 \times 36.5 = 14600$ calories.

This has been given out by 25.7 gm. of steam turning into water and then cooling from 100° C. to 48.5° C., *i.e.* 51.5° C. During the latter process $25.7 \times 51.5 = 1323.55$ calories have been given out.

Hence, 25.7 gm. of steam in condensing without change of temperature give out $14600 - 1323.55$ calories, *i.e.* 13276.45 calories.

Hence 1 gm. of steam in condensing gives out $\frac{13276.45}{25.7} = 516.6$ calories, *i.e.* the latent heat of vaporization of water $= 516.6$.

PART III

DYNAMICS

CHAPTER I

MEASUREMENT OF FORCES

DYNAMICS deals with *forces*, their measurement, and their effects. The force with which we have most to do is that with which the earth draws all bodies towards itself, or *gravity*. The force with which any body is drawn down towards the earth is called the *weight* of that body. The weight of a body varies slightly as we take it to different places on the surface of the earth, being greater as we go further from the equator. This variation is, however, so slight that for most purposes it is neglected.

Since gravity is a force which is always available, it is convenient to use it as a means of measuring other forces. This is done by balancing the force to be measured against the weight of a given body. For example, if we hang a stone by means of a string, we say that the force exerted by the string in keeping up the stone is equal to the force exerted by the earth in pulling down the stone, *i.e.* is equal to the *weight* of the stone. The *unit of force* which we use in this course is the weight of 1 gm., written 1 **gmwt.**

Dynamometer.—An instrument for measuring forces is called a *dynamometer*.[1] A simple form of dynamometer consists of a spiral steel spring, as in Fig. 52, fixed at one end to one end of a block of wood, and fitting loosely in a groove in the block. At the free end of the spring, attached to it by means of a swivel, is a hook carrying a piece of brass with an arrow marked on it. The force exerted in stretching the spring to any extent is read off by noting the position of the arrow-head on a scale on the side of the groove graduated in gmwt. The further the spring is stretched the greater is the force exerted in stretching it. In using the dynamometer, care must be taken that it is held in such a position that the force to be measured acts exactly along the groove. As the spring of the dynamometer is apt to be lengthened permanently if stretched too far, it is important to take care that it is not stretched beyond the lowest mark on the scale. It is also convenient to have the upper end of the spring fixed to a block of wood which can be moved up and down the groove, so that before beginning any experiment in which the dynamometer is used the arrow-head may be adjusted to the zero mark on the scale when the spring is unstretched. When this is done, it is very improbable that any considerable error will be found to exist in any other part of the scale.

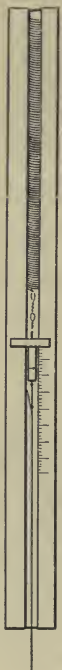

Fig. 52.

[1] This word is also often applied to an instrument used for measuring the *work* done by an agent, *e.g.* the work done by a horse in drawing a waggon.

EXPERIMENT 1

To test a dynamometer.

The dynamometer is tested by placing it in a retort-stand clamp so that the spring hangs vertically, and then hanging by the hook a scale pan of known weight. Weights are added to the pan till the total weight (*i.e.* the force stretching the spring, and therefore the force exerted by the spring) is 100, 200, 300, etc. gmwt., and noting whether the arrow-head is at the corresponding mark on the scale. If it is not, the graduation is inaccurate, and a table must be drawn up showing the real weight needed to bring the arrow-head to each division. The following is an example of such a table :—

Apparent force .	50	100	150	200	250	300	350
Real force . .	45	100	150	210	254	296	350

(Note the number of the dynamometer.)

FRICTION

Friction is the name given to the force which always exists when one body slides over another, tending to oppose the motion.

EXPERIMENT 2

To prove that friction is (up to a certain point) a force which can change its amount so as to balance any force tending to cause motion.

Take a block of wood with a small staple fixed in the centre of one face, and attach the hook of the dynamometer to the staple, pull the dynamometer away from the block slightly till the force applied is about 10 gmwt. The block

does not move. Since the block does not move and yet force is being applied to it, what is preventing the motion? What is the amount of the force of friction in this case?

Pull the dynamometer further and so increase the force acting on the block to 20 gmwt. Go on increasing the force each time by 10 gmwt. and recording your result.

You will find that at last the block moves. Thus the force of friction had successively various values till at last it could increase no more.

Try this experiment several times, and see whether the block always begins to move for the same amount of force, and record the result in each case.

The force that just causes the block to start must obviously be equal to the greatest force which friction can exert in this particular case. For this reason it is called the *limiting force of friction*, because the friction cannot exceed this limit.

Two kinds of friction.—Instead of noting the force required to *start* the block moving, find what force must be exerted by the dynamometer in order just to *keep* it moving after it has been started. You will find that the latter force is smaller than the former, so that the force needed to overcome friction (and therefore the force of friction) is greater when the surfaces are at rest than when they are already in motion.

As a rule it will be found that more uniform results are obtained if the friction measured in the following experiments is that which is called into play when the surfaces are in motion. Thus in measuring the force of friction in any of the following experiments it will be well to start the block moving with one hand while pulling the dynamometer with the other. This is not essential, however; what *is* essential is that the same kind of limiting friction be measured in every case.

Note.—In this, as in other experiments on friction, the experiment should always be done on the same part of the table, and this should always be marked in some way. Otherwise, the variations in the character of the surface of the table from point to point will prevent concordant results being obtained. It is still better to use, instead of the table itself, a flat piece of hard wood carefully planed, when good results are wanted.

EXPERIMENT 3

Does the force of friction depend on the area of the surfaces in contact, when other things remain the same?

To answer this, repeat the former experiments, placing the same block on each of the four faces in succession. Record your results thus, but taking care that for each face you must measure the friction at least four times, and always use the same part of the table.

Area of Side on which Block Rests.	Force of Friction.				Average.
	1.	2.	3.	4.	
Sq. cm.					
,, ,,					
,, ,,					
,, ,,					

What answer must be given to the question?

EXPERIMENT 4

Does the force of friction depend on the pressure between the surfaces? If so, how does it vary?

To answer this you must have some means of varying the pressure between the blocks and table. The easiest way to do this is to place on the top of the block various

weights, so as to make the total weight of the block and weights (and therefore the pressure on the table) equal to some convenient number of gmwt. say, 100, 200, 300, etc. Measure in each case the friction, and record your results thus :—

Pressure.	Friction.				Average Friction.
	1.	2.	3.	4.	
100 gmwt.					
200 ,,					
300 ,,					
400 ,,					
500 ,,					
etc.					

Answer the following questions :—

1. Does the force of friction increase or diminish as the pressure increases?

2. Does the force of friction increase at the same rate as the pressure increases, *i.e.* does the friction increase by equal amounts when the pressure increases by equal amounts?

3. In each of the lines in above table, work out the result got by dividing the friction by the pressure.

4. What, then, is the relation between the friction and the pressure? (See p. xvi. Test for Proportionality.)

The ratio $\frac{\text{friction}}{\text{pressure}}$ being constant for the same two surfaces is called the **coefficient of friction** of the two surfaces.

Draw on a sheet of squared paper a curve connecting the friction with the pressure, taking abscissæ to represent pressure and ordinates friction.

It will be found that the curve is a straight line.

EXPERIMENT 5

In the same way as in last experiment find the coefficient of friction of wood on glass.

For this experiment it is well to use a slab of plate glass, which should be kept for the purpose, and which can be prevented from slipping on the table by means of pins.

Draw the curve connecting pressure and friction for this experiment on the same sheet of paper as you used in last experiment.

EXPERIMENT 6

Friction of cords.

Hang to one end of a string a 100 gmwt., and to the other end attach the hook of your dynamometer. Allow the string to hang over a glass tube or rod about 1 cm. in diameter, fixed horizontally in your retort-stand clamp, as in the figure. Note the reading of the dynamometer when the weight is just slipping down, and similarly when you are pulling it up. If there were no friction, the force exerted by the dynamometer would in each case be 100 gmwt. But on account of the friction, the force exerted by the dynamometer in the first instance will be less than 100 gmwt., and in the second case greater. What, then, is the value of the force of friction in each case?

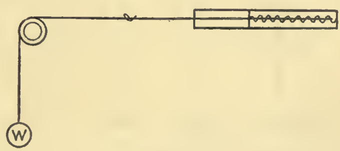

Fig. 53.

Do this when the angle between the one part of the string and the other part produced (*i.e.* the angle through which the string is bent) is 45°, 90°, 135°, 180°, 225°,

270°, etc., estimating the angle roughly by the eye, and note the results, thus:—

Angle	45°	90°	135°	180°	225°	270°	315°
Force needed just to prevent slipping down							
Friction							
Force needed to pull weight up							
Friction							

Plot on a piece of squared paper the results of this experiment, making abscissæ to represent angle and ordinates to represent the forces in second and fourth line. It

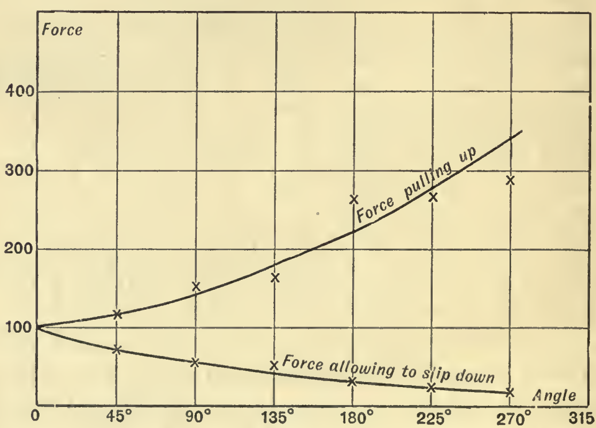

Fig. 54.

will be convenient to represent 45° by the distance between two thick lines on your squared paper, and 100 gmwt. by the same distance.

Draw smooth curves so as to pass as near as possible to all the points you have plotted, and the result will be probably like Fig. 54.

From the upper part of the curve it will be noticed that the force needed to pull the weight up increases very rapidly with the amount of string in contact with the tube, and is not proportional to it.

This fact is made use of by sailors when they wish to check the motion of a ship, *e.g.* in drawing in to a pier. A rope attached to a post on shore is coiled two or three times round a post on the ship, and the friction is so great that a man holding the free end of the rope is able to check the motion and gradually to stop it.

In doing this experiment, care must be taken that the string and the glass are both perfectly clean, and the same portions of string and glass should be used as far as possible in making each measurement.

Experiment 7

Effect of size of tube.

Repeat Experiment 6, using a much wider tube than before. Tabulate your results, and draw the curves in the same way as in last experiment, and state, as a result of your measurements, what the effect of increasing the size of the tube or rod is, so long as the angle through which the string is bent remains the same.

As it is almost impossible to ensure that the condition of the surface of the glass is the same in both cases, no great reliance can be placed on the result of a single set of experiments. In some cases the wide tube will be found to give greater friction, and in others the narrow tube. What is of importance is that the student should state the result of his own experiments without regard to any preconceived notions he may have on the subject.

* Experiment 8

Relation between friction and angle through which string is bent.

We have seen that the relation between friction and angle in the previous experiments is not that of simple proportion. It can be proved that it is much more complicated than this, and the actual relation is that the

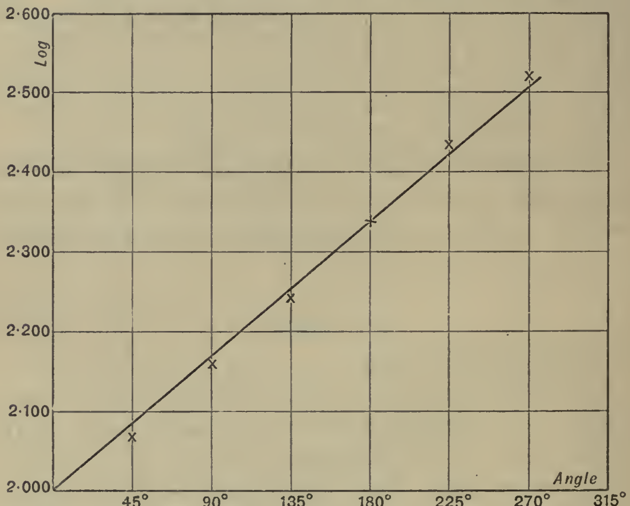

Fig. 55.

logarithm of the force needed to pull up a given weight increases uniformly with the angle through which the string has been bent. Though you may not yet understand what a logarithm is, it will be useful for you to find out from a table the logarithms of the forces measured in Experiment 6 required to pull up the 100 gmwt.

But, as you have drawn a smooth curve so as to be as near as possible to the points obtained by plotting your

results, it will be better for you to take the values of the forces for every 45° obtained by noting the points where the smooth curve cuts the vertical lines indicating every 45°. The reason for this is that you are likely in this way to avoid large experimental errors, which are very apt to be made in this kind of measurement. In this way you can find with fair accuracy the force needed to pull up the 100 gmwt. at various angles, and thus draw up a second (corrected) table, thus :—

Angle	0°	45°	90°	135°	180°	etc.
Force needed to pull up 100 gmwt. . .	100	117	148	178	220	etc.
Logarithm of numbers in last line . .	2.000	2.068	2.170	2.250	2.342	etc.

Then draw the curve connecting angle with logarithm of force needed to pull weight up, taking the same abscissæ as before, and marking the thick lines on the axis of ordinates 2.000, 2.100, 2.200, 2.300, etc. In this way we get a series of points, and on drawing a smooth curve to go through all of them as nearly as possible, you will find that it is a straight line, showing that the logarithm increases by equal amounts where the angle increases by equal amounts.

Experiment 9

Pulleys.

Repeat Experiment 6, but instead of using a glass tube use a pulley; drawing up a table in the same way as before.

Explain the great difference between the amount of friction called into play in the former experiments and in this.

Does the friction increase with the angle through which the string is bent?

What is the use of a single pulley used in this way?

You will notice that by its means the direction of a force can be altered without diminishing the amount of the force to any appreciable extent, whereas if a fixed cylinder be used the friction is so great as to make its application to practical purposes useless except in some special cases.

EXPERIMENT 10

Combination of pulleys.

Although a single pulley only enables us to alter the direction of a force, we can gain much mechanical advantage by using pulleys in combination.

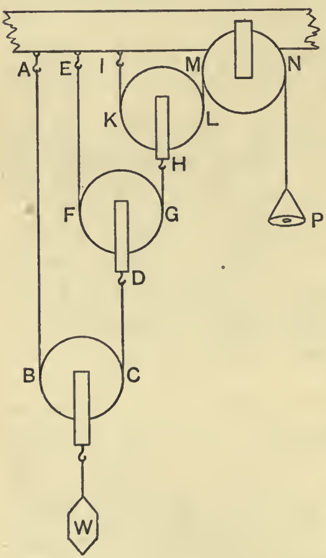

Fig. 56.

There are several ways of doing this, one of which is shown in the diagram.

Without trying any experiment, answer the following questions:—

Assuming the pulleys to be without weight, and supposing a weight of 200 gm. to be at W.

1. What is the force exerted by the string AB and what by CD?

2. What, therefore, is the force pulling down at D?

3. What is the force pulling down at H?

4. What is the force exerted by LM?

5. What is the force at P necessary to prevent W from falling down?

Having answered these questions, test their accuracy by setting up the pulleys and, before hanging on W, attaching at P a light scale pan. Then put a pill-box with shot in this pan, and adjust the shot so that the whole is balanced. Then hang on a 200 gmwt. at W, and place in the scale pan the weight which you found as the answer to question 5.

* Experiment 11

Find what weights must be put in P.

(1) just to overbalance W and cause it to rise;

(2) to allow W just to fall;

and thus find the effect of friction on this combination of pulleys.

What force would be needed just to balance 200 gm. at W, if there were 2, 4, 5 movable pulleys instead of 3? This is to be answered without trying the experiment, but by using the same reasoning as in Experiment 10.

CHAPTER II

FORCES IN DIFFERENT DIRECTIONS

EXPERIMENT 12

Parallelogram of forces.

If two forces act at a point in different directions they are equivalent to a single force (called their *resultant*), whose magnitude and direction can be found by the following principle called the parallelogram of forces: "**If two forces acting at a point be represented in magnitude and direction by two straight lines, then their resultant will be represented in magnitude and direction by the diagonal (drawn through that point) of the parallelogram constructed on these two straight lines as adjacent sides.**"

Draw in your note-book lines representing in magnitude and direction the following forces: 58 gmwt. N. and 126 gmwt. E., and find their resultant by the use of the principle just described. The scale of your diagram may be any you please, *e.g.* you may represent 1 gmwt. by 1 mm. or by 2 mm. or by any other length you choose, only you must use the same scale for all the forces in any one diagram.

To prove the proposition, take two dynamometers and a 200 gmwt., clamp the dynamometers in two retort-stands, and place the hooks of the dynamometers in a loop

at one end of a string at least 8 cm. long, at the other end of which is fastened your 200 gmwt. Adjust the dynamometers in such a way that the pull on them is perfectly straight, and note the force exerted by each. Then take a piece of paper or cardboard and, holding it behind and close to the strings, mark their direction on it.

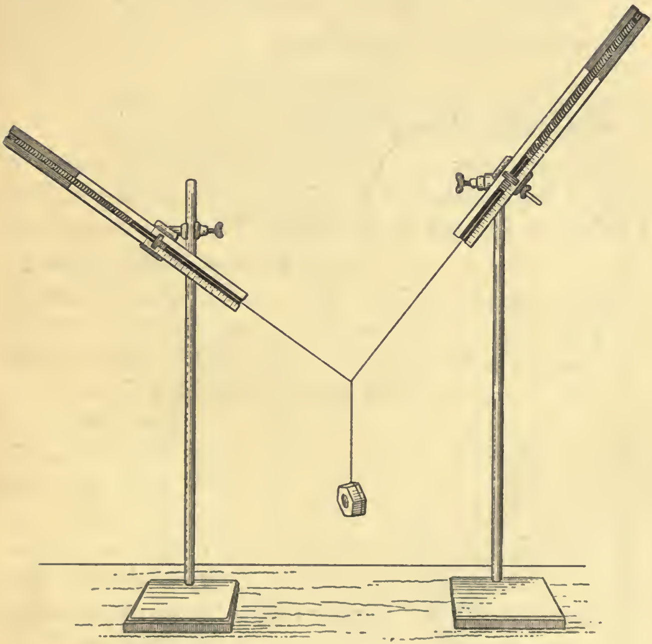

Fig. 57.

(This is best done by making with a pencil two dots on the paper so as to be covered by each string.) Write down along each line the force exerted in that direction, and measure off on each (starting from the junction of the strings) a length proportional to the force. Complete the parallelogram on any two of them. If the proposition is true, the

diagonal of the parallelogram should be in a straight line with the third force, and the length of the diagonal should be equal to the length of the line representing the third force. This is because the third force must be equal and opposite to the resultant of the first two, else the system could not remain at rest.

Experiment 13

Application of the principle.

Without trying any experiment, find by means of a diagram the horizontal force which will be needed to draw a weight of 200 gm. at the end of a string 1 metre long a distance of 40 cm. from the vertical; AO = 1 metre, ON = 40 cm. (See Fig. 58.)

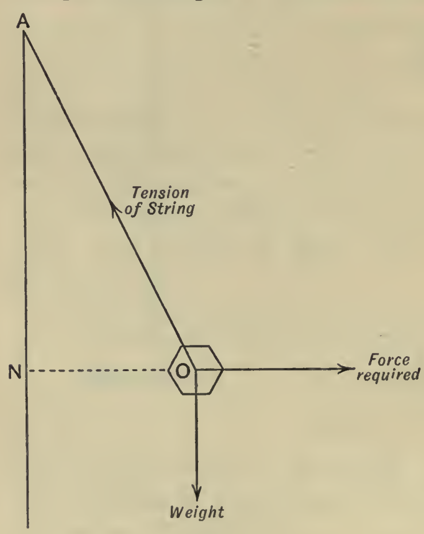

Fig. 58.

Draw first a diagram, like Fig. 58, to scale (a convenient scale is 1 mm. to 1 cm.). This diagram only shows the *directions* of the three forces concerned.

Then, since the three forces are in equilibrium, the resultant of the tension of the string and the horizontal force must be equal and opposite to the weight. Therefore the resultant of

these two unknown forces must be vertically upwards through O, and must be equal to 200 gmwt.

Produce the direction of the weight upwards, and cut off from it a distance to represent 200 gmwt. on any convenient scale (say 1 mm. to 2 gmwt.). Through the end of this line draw lines parallel to the other two forces, thus drawing the parallelogram of forces. Measure the horizontal side of this parallelogram, and thus find the horizontal force required.

How could you find the tension of the string (*i.e.* the force which the string exerts along the direction OA)?

EXPERIMENT 14

Application to inclined plane.

Find, as in last experiment, the force which is needed to keep a roller weighing 100 gm. from rolling down an inclined plane, the length of the plane being 10 cm., and its height 3 cm. (the force acting along the plane).

Let O be the centre of the roller and let a force F act on it parallel to the plane; we wish to find the value of F in order that the roller may be kept at rest, there being supposed to be no friction between roller and plane.

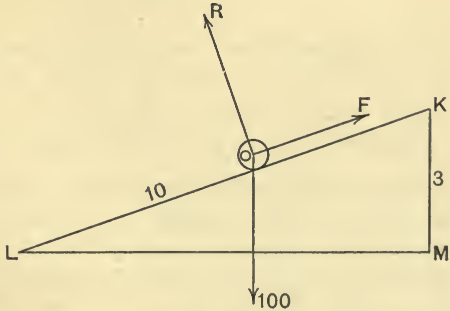

Fig. 59.

Here, again, we see that the resultant of F and R must be equal and opposite to the weight of the roller. Draw the

diagram carefully to scale, and then draw the parallelogram of forces, and thence find what F is and also what R is.

Why do we assume that R acts at right angles to the plane?

Inclined Plane

Suppose we have a body of any weight W resting on a smooth inclined plane of any slope, such as KLM, we can prove that the force parallel to the plane required to keep the body from slipping down bears the same proportion to the weight of the body that the height of the plane does to its length.

The forces acting on the body to keep it at rest are

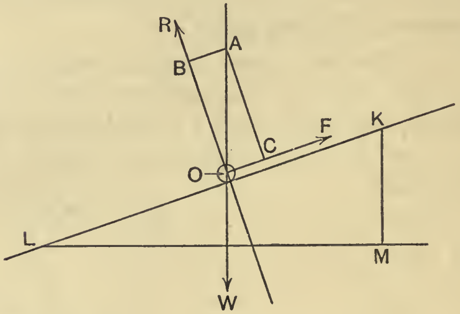

Fig. 60.

three, viz.: the weight W of the body vertically downwards, the force F acting parallel to the plane, and a force R exerted by the plane preventing the body from sinking into the plane and, since the plane is smooth, therefore acting perpendicularly to the plane.

Since these three forces keep the body at rest, the resultant of any two of them must be equal and opposite to the third. Hence the resultant of F and R must be equal to W and opposite to it, *i.e.* vertically upwards.

Draw OA vertically upwards and cut off a length OA to represent W on any scale. Complete the parallelogram OBAC. Then on whatever scale W is represented by OA, F will be represented by OC and R by OB on the same scale.

Hence F bears the same proportion to W that OC bears to OA or

$$\frac{F}{W}=\frac{OC}{OA}.$$

But OC bears the same proportion to OA that KM does to KL, because the triangles OAC and KLM are similar to one another, or

$$\frac{OC}{OA}=\frac{KM}{KL}.$$

Hence

$$\frac{F}{W}=\frac{KM}{KL}$$

or *the force required bears the same proportion to the weight of the body as the height of the plane bears to its length.*

Experiment 15

To prove experimentally that the force parallel to a smooth inclined plane required to keep a body at rest on the plane is the same fraction of the weight of the body as the height of the plane is of its length.

As we cannot get a *smooth* inclined plane, we take a plane as smooth as we can and use a heavy roller as the body to be experimented on. The roller is a metal cylinder, having an axle at each end. A piece of wire, bent as in the diagram (Fig. 61), enables the roller to be attached to the hook of the dynamometer. Weigh the roller, then make an inclined plane with blocks, as in Fig. 62, and attaching the dynamometer hook to the roller, find the force needed to keep the roller at rest, the

dynamometer string being kept parallel to the inclined plane. In order to avoid any error due to friction, it is

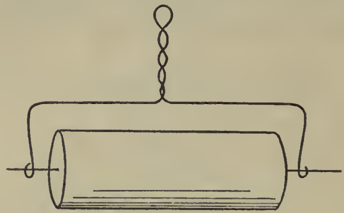

Fig. 61.

well to notice the force needed to pull the roller up, and that which just allows it to slide down and take the mean of the two values.

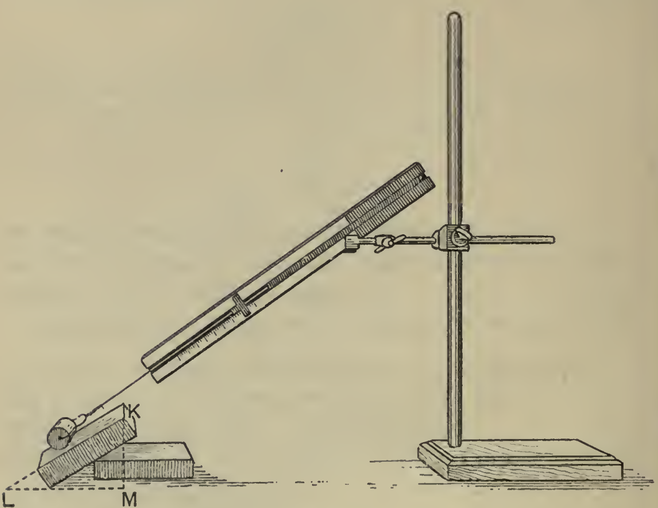

Fig. 62.

Measure the height KM and length LM of the plane, and calculate what the force ought to be according to the

statement proved above. Do the same for a different inclination of the plane, and write down your results in tabular form thus :—

Weight of Roller.	Height.	Length.	Wt. $\times \frac{\text{height}}{\text{length}}$.	Force Measured.

EXPERIMENT 16

Friction on an inclined plane.

Take a plane slab of wood and place on it a wooden block. Raise one end of the slab gradually until the block slips down. Repeat this several times, noting the height to which the slab is raised each time.

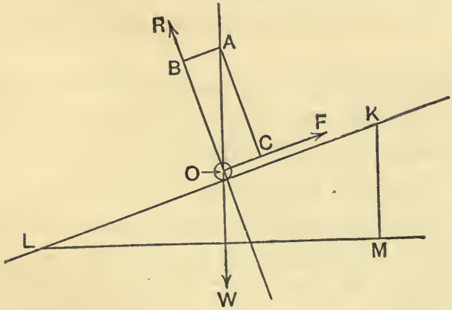

Fig. 63.

When the block just begins to slide, it is evident that the force of friction acting up the plane is just equal to the limiting value of friction for these two surfaces. Hence,

when the block is just on the point of slipping, we have these three forces acting on it: (1) its own weight W vertically downwards; (2) the force of friction F parallel to the plane tending to prevent the block sliding; (3) the pressure R of the plane at right angles to the plane. The coefficient of friction being the ratio $\frac{\text{friction}}{\text{pressure}}$, it can be seen from Fig. 63 that if W is represented by OA, then R is represented by OB and F by OC and therefore coefficient of friction $= \frac{OC}{OB} = \frac{OC}{CA}$.

But since OAC and KLM are similar triangles

$$\frac{OC}{CA} = \frac{KM}{ML}.$$

Now $\frac{KM}{ML}$ or $\frac{\text{height of plane}}{\text{base of plane}}$ is commonly called the "gradient"[1] (generally stated thus, "1 in 20," "1 in 5," "1 in 100"). Hence the coefficient of friction between two substances is equal to the gradient of a plane made of one of these surfaces, when a block, having the other substance for its under surface, is just on the point of slipping.

Use this method for finding the coefficient of friction of wood on wood and of wood on glass, expressing the result in each case as a decimal fraction correct to two places.

[1] Sometimes this word is used to denote the ratio of height of plane to length of plane, *i.e.* $\frac{KM}{KL}$, but the meaning given above is that in which it is generally used.

CHAPTER III

MOMENTS

Experiment 17

To show that the turning power of a force is proportional to the distance of its line of action from the axis.

It is obvious that the power which a force has to turn a body depends on the place at which the force is applied, and on the direction in which the force is exerted. For example, it is most easy to shut a door by pushing it at a point as far from the hinges as possible, and by exerting the force at right angles to the plane of the door.

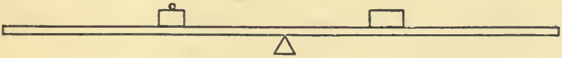

Fig. 64.

Take a metre measure and balance it on the edge of a triangular file. Take three pill-boxes and pour enough shot into each to make each weigh 50 gm. Place one of the pill-boxes on the metre measure, about 10 cm. from the edge of the file (the edge of the file is the axis or *fulcrum* round which the beam can turn). On the other side of the fulcrum place a 50 gmwt., and move it about till the beam balances again. Measure the distance of the centre of this weight from the fulcrum.

Next place a second pill-box on the top of the first and move the 50 gmwt. till the beam balances, and again measure the distance from the fulcrum as before.

Repeat the experiment after putting the third pill-box on the top of the other two.

The turning power of the 50 gmwt. must in each case be the same as that of the pill-boxes. Hence the turning power of the 50 gmwt. in the second case must be twice as great as in the first, and in the third case three times as great.

State whether the turning power of the 50 gmwt. is proportional to the distance of that weight from the axis.

Definition of moment.—*The product of a force into the distance of its line of action from a point is called the* **"moment of the force about that point."**

It must be noted that whenever we speak of the *distance* of a line from a point, we mean the length of the *perpendicular* drawn from the point to the line or the line produced. Thus in Fig. 65, PM is the distance of the line AB from the point P.

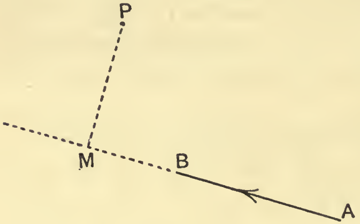

Fig. 65.

Thus the moment of a force about any point is the measure of its power of turning a body about that point.

Note.—The best way of finding the position of the centre of the weight is to note the division on the scale at each side of the weight and take the mean of these two measurements. It will probably be found that the beam cannot be made to rest horizontally, but the conditions are nearly enough satisfied when it rests equally well with either end down.

EXPERIMENT 18

When any number of forces act on a body their turning power is measured by the sum of their separate moments.

Balance your metre measure as in last experiment. On the right-hand side place several weights at different distances from the fulcrum. On the other side place a single weight so as to make the beam balance again.

Measure and record the distance of the centre of each weight from the fulcrum, and calculate the moment of each. Then write down :—

Sum of moments of weights on right-hand side =
Moment of weight on left-hand side . . =

EXPERIMENT 19

Find by the principle of moments the weight of one of your brass cylinders by balancing it on a half-metre measure against a 50 gmwt.

This you do by writing down moment of brass cylinder, which must be equal to moment of 50 gmwt. Then, knowing the moment of the cylinder and its distance from the axis, find the weight of the cylinder.

Test the accuracy of your result by weighing the cylinder in the balance in the usual way.

EXPERIMENT 20

The balance—ratio of the arms.

The balance is simply a lever, the weight of a body being compared with that of standard pieces of metal. In a good balance the arms ought to be equal to one another, if they are not, the true weight of an object will not be

directly given. If they are not equal, the balance may still be used for weighing bodies if the ratio of the length of one arm to the other is known.

To find this ratio; let L be the length of the left and R of the right arm of the balance. Make the balance exactly even with shot and paper in the usual way. Put a 50 gmwt. in the right-hand pan, and in the left place a pill-box containing enough shot and paper to restore the equilibrium. Call this pill-box No. 1—its true weight will not be 50 gm. unless the arms of the balance are equal.

Take out the 50 gmwt. leaving No. 1 in the left pan. Then put in the right pan a second pill-box, with shot to balance No. 1. Call this No. 2.

What is the true weight of No. 2 even if the arms are unequal?

Remove No. 1 and put the 50 gm. weight in its place. Restore equilibrium by weights out of your box.

Write down the moment on each side thus:—

Moment on left-hand side = L × weight on that side.
,, right-hand side = R × weight on that side.

Since the balance is in equilibrium these must be equal to each other.

From this equation find $\frac{R}{L}$.

Draw three diagrams in your note-book, showing the forces in each of the three cases in which the balance was in equilibrium.

If the arms are unequal, what must you multiply the apparent weight by in order to get the true weight?

Note.—The object to be weighed is placed in the left-hand pan and the weights in the right.

Example. — In a certain balance $\frac{R}{L} = 1.0012$, what is the true weight of an object whose apparent weight is 22.163 gm.?

EXPERIMENT 21

Forces acting in different directions.

Take your half-metre measure and place round it near one end an indiarubber band. Attach the hook of

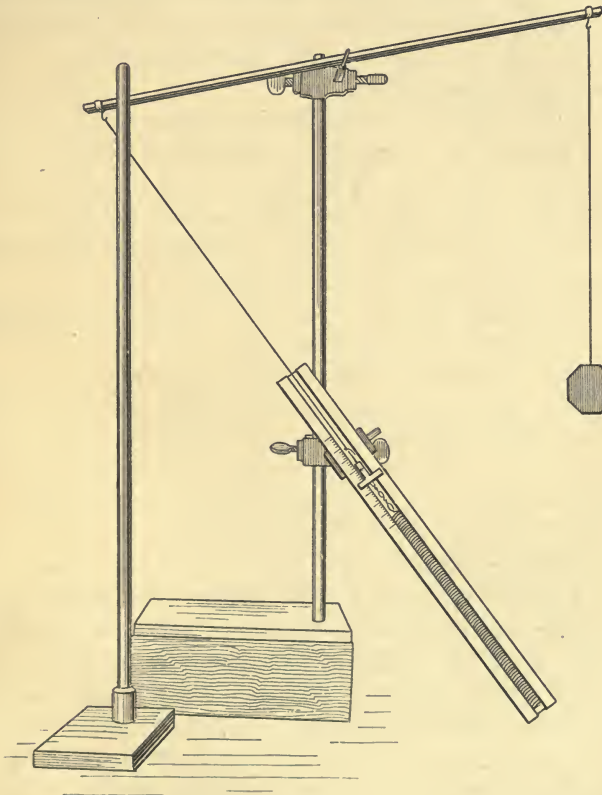

Fig. 66.

your dynamometer to this band, and to the other end of the measure hang a 200 gm. weight. Fix a triangular file

to the clamp of your retort-stand, and balance the half-metre measure about its middle point on the edge of the file as in the diagram (Fig. 66). The direction of the dynamometer string and of the half-metre measure may be any you please, so long as the middle point of the measure is on the edge of the file. The dynamometer should be fixed in another clamp of your retort-stand in order that you may be able more easily to make the required measurements.

Note carefully the force exerted by the dynamometer and measure as accurately as possible the perpendicular distances from the edge of the file to the dynamometer cord and to the string carrying the 200 gm. weight.

What is the moment of the 200 gmwt. about the edge of the file? (See p. 136 and Fig. 65.)

What is the moment of the force exerted by the dynamometer about the edge of the file?

Note.—You will probably find it desirable to have another retort-stand placed, as in the figure, to prevent the lever swinging sideways.

* Experiment 22

Law of tangents.

A special application of the equality of moments is so important in the study of electricity that it is worthy of being considered by itself. Suppose we have a body which can turn freely about an axis, such as a magnetic needle, and suppose we have two forces acting at right angles to each other at one point of the body, say the end of the needle, the position in which the needle comes to rest will depend on the relative magnitudes of the two forces.

Thus, let SN represent a bar which can turn about an axis at O, and let two forces H and F act at N at right

angles to each other. Through O draw OA parallel to the direction of one of the forces H, and produce FN backwards to meet OA in B. Then if the body is at rest the moment of F about O must be equal to the moment of H about O. Therefore

$$F \times OB = H \times NB,$$

and therefore

$$F = H \times \frac{NB}{OB}.$$

Now, the fraction $\frac{NB}{OB}$ is the *tangent* of the angle AON.

$$\therefore\ F = H \tan. AON,$$

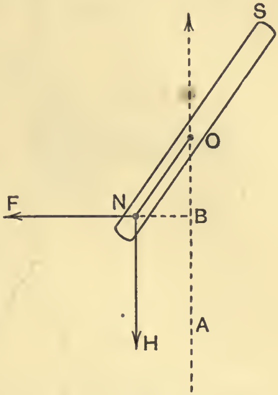

Fig. 67.

hence

$$\frac{F}{\tan. AON} = H,$$

and if H is constant F *is proportional to* tan. AON. This is the principle of the tangent galvanometer.

To verify the law of tangents.—Take a bar of wood NS, with holes bored through it at its middle point O, and at N near one of its ends. Then take a circular card graduated in degrees, and having a cork glued to it at the centre of the circle, with a small hole bored through the cork in such a way that when a knitting needle is passed through this hole the needle will turn with a good deal of friction in the cork, and will be at right angles to the card through its centre. (See Fig. 68.)

Fix the knitting needle horizontally in the clamp of your retort-stand, and then put the bar NS on the projecting piece of the needle, so that the bar can turn freely about O as an axis. Fasten a sewing needle at the end of the bar at N

or S so as to be in the straight line NOS, and of such a length that it reaches to the graduations on the card. (See Fig. 69.) Attach a 100 gmwt. to N, and when it is hanging freely turn the card round until the needle points to "O" on the scale.

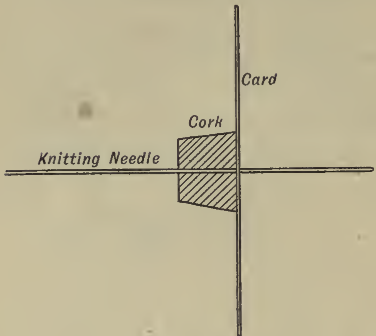

Fig. 68.

Then attach your dynamometer hook to a second cord passing through N, and, keeping the pull of the dynamometer horizontal, draw N aside

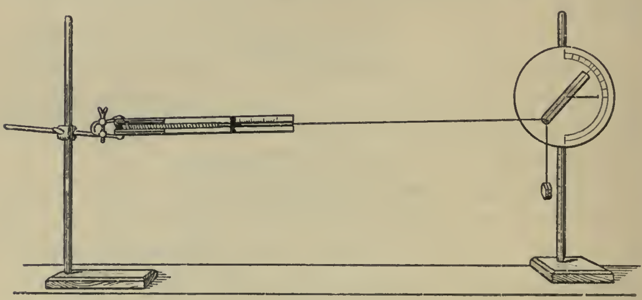
Fig. 69.

till the needle points to 5° on the scale, and note the force exerted by the dynamometer.

Then draw the dynamometer further away from the needle (at the same time raising it to keep the force exerted by it horizontal) until the needle points to 10° on the scale, and note the force exerted. Repeat this, increasing the deflection of the needle by 5° each time,

and record the results in tabular form as follows. The second column contains the tangents of the angles in the first column correct to two places of decimals.

Angle of Deflection.	Tangent (Angle of Deflection).	Pull of Dynamometer.
5°	.09	
10°	.18	
15°	.27	
20°	.36	
25°	.47	
30°	.58	
35°	.70	
40°	.84	
45°	1.00	
50°	1.19	
55°	1.43	
60°	1.73	
65°	2.14	
70°	2.75	
75°	3.73	
80°	5.67	

On a sheet of squared paper plot the above results, making abscissæ to represent tangents and the ordinates to represent force exerted by dynamometer. If the experiment has been accurately done these points should lie on a straight line, passing through the point of intersection of the axes, thus showing that the horizontal force is proportional to the tangent of the angle of deflection.

CHAPTER IV

PARALLEL FORCES

Resultant of two parallel forces.—Suppose a body to have two parallel forces acting on it as P and Q acting at points A and B, then this body can only be kept at rest by a force acting at some point of the body, such as C, parallel to P and Q, but in the opposite direction.

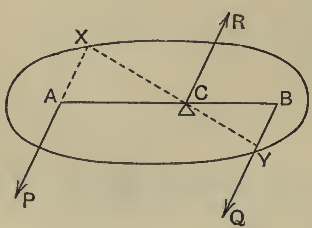

Fig. 70.

These three forces, P, Q, and R, keeping the body at rest, we see that any one of them must be equal and opposite to the resultant of the other two.

Thus R	is equal and opposite to the resultant of				P and Q.
,, P	,,	,,	,,	,,	Q and R.
,, Q	,,	,,	,,	,,	P and R.

It can be shown, both theoretically and by experiment, that $R = P + Q$; and since the body is at rest the moment of P about C must be equal to the moment of Q about C. Hence

$$P \times CX = Q \times CY, \text{ or } \frac{P}{Q} = \frac{CY}{CX},$$

where CX and CY are drawn perpendicular to the forces. But by similar triangles ACX, BCY

$$\frac{CY}{CX}=\frac{CB}{CA}.$$

Hence

$$\frac{P}{Q}=\frac{CB}{CA}.$$

Hence the resultant of two like parallel forces is equal to the sum of the forces, and the point at which it acts divides the distance between the points of application of the two forces in the inverse proportion of the forces.

Unlike Parallel Forces

Looking at the diagram, it is obvious that just as R is equal and opposite to the resultant of P and Q, so is Q equal and opposite to the resultant of P and R. Hence it follows that the resultant of two unlike parallel forces is equal to their difference.

Again, since the three forces P, Q, and R produce equilibrium, it follows as before that the moments of R and Q about A must be equal and opposite to each other. Hence

$$\frac{AB}{AC}=\frac{R}{Q}.$$

Hence the point of application of the resultant of two unlike parallel forces is found by the same rule as that of two like parallel forces, the only difference being that in the latter case the resultant is not between the two forces but outside of them.

Couple

There is one case in which unlike parallel forces have no resultant, *i.e.* when they are equal to each other. The combination is called a "**couple,**" and has no effect in moving the body as a whole, but only in turning it round.

Experiment 23

To prove by experiment that the resultant of two parallel forces in the same direction is equal to the sum of these forces.

Support your half-metre measure (by means of an india-

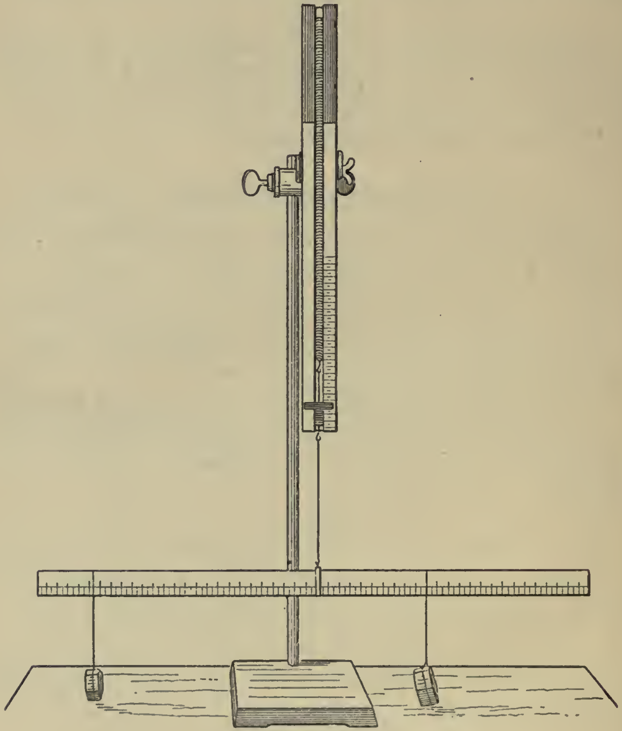

Fig. 71.

rubber ring placed at its centre) to the hook of your dynamometer, which is clamped in your retort-stand, as in the diagram, and note the pull on the dynamometer exerted by the measure itself.

Attach two weights, say 100 gm. and 50 gm., to pieces of string, with loops which can pass over the measure, and adjust these weights so that the measure is balanced horizontally.

You will find that the dynamometer now indicates a pull which is 100 + 50, or 150 gmwt. greater than before.

Measure and record the distance of the two weights from the centre of the measure, and state whether the statement just made as to the *position* of the resultant is true.

Repeat the experiment with two other weights, and describe the result.

Centre of Gravity

Every particle of any body is always acted on by a force pulling it vertically downwards. This force is called the *weight* of the particle. Thus, we must imagine that every body on the earth's surface is being acted on by an

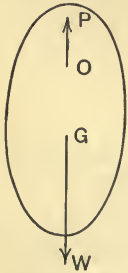

Fig. 72.

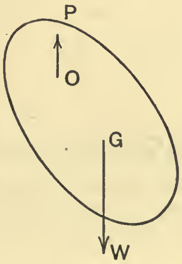

Fig. 73.

immense number of parallel forces. Now, all these parallel forces have a single resultant, which is called the *weight of the body*, and in whatever position the body is held this resultant always passes through a certain point, which is called the Centre of Gravity of the body.

From what has been said, it will be seen that if a body be suspended at any point it cannot rest until the centre of gravity of the body is vertically under the point of support.

Thus in Fig. 72 the centre of gravity G being vertically under O when the body is supported, the weight acting downwards at G is exactly balanced by the pressure of the support acting upwards on the body at O. But the position in Fig. 73 cannot be maintained, for the weight W and the pressure P, though acting in opposite directions, are not in the same straight line, and so the body will be turned in the direction of the hands of a watch.

Experiment 24

Centre of gravity of uniform beam.

The centre of gravity of a straight beam of uniform thickness is obviously the centre of the beam. Try with your metre measure whether this is so. If the C.G. is not at the "50" mark on your metre measure, the measure cannot be uniform. Note carefully the position of the centre of gravity of the measure for future reference.

Experiment 25

To find the weight of a beam by balancing it about some point not its centre of gravity.

Lay your half-metre measure so as to rest on the edge of the triangular file, not at its middle point, but at a distance of 10 cm. or more from it. Place a 50 gmwt. on the lever, and adjust its position until the lever is just balanced on the edge of the file, as in the diagram.

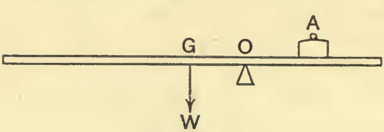

Fig. 74.

Measure and record the distance from centre of gravity of lever to fulcrum, and the distance from centre of 50 gmwt. to fulcrum.

What is the moment of the 50 gmwt. about the fulcrum?

What, therefore, must be the moment of the weight of the lever about the fulcrum?

At what distance from the fulcrum does the weight of the lever act?

What, therefore, is the weight of the lever?

Weigh the lever in the balance in the ordinary way, and record the result.

* Experiment 26

Lay your metre measure on a file, but not at its centre of gravity; place various weights on the lever at various distances from the fulcrum on each side, so as to make the lever balance, and add up the moments on each side, including the moment of the weight of the lever, and find out whether they are equal.

Experiment 27

To find the centre of gravity of a plane lamina.

Cut out of stout cardboard a triangle of any shape, and pierce holes in it X, Y, Z at any three places. Then hang the card by a pin passing through one of these holes X, and fixed in the side of the table in such a way that the card can swing quite freely. Hang from the pin in front of the card your plumb-line by a loop, as in Fig. 75, and mark with a sharp-pointed pencil a number of dots on the card where the plumb-line hangs, and as near to the lower edge of the card as possible. Then note, by the help of these dots, the exact point where the plumb-

line meets the row of dots. Remove the card and draw on it a sharp pencil-line, showing as exactly as possible the direction of the plumb-line when the card was hung from X.

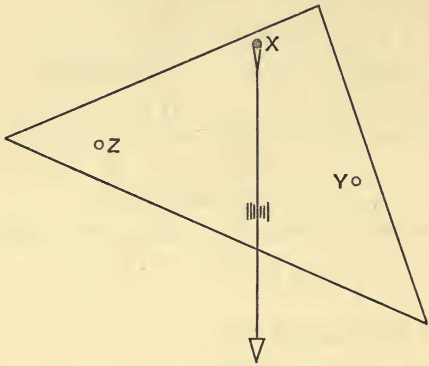

Fig. 75.

Repeat this, hanging the card from Y, and again from Z.

If the experiment has been correctly done, these lines should all intersect in the same point, and at that point is the centre of gravity of the triangle, half-way between the two surfaces of the card.

Test the correctness of your result by trying whether the card will balance on the point of a pin stuck in the point you have found.

The points X, Y, and Z should be chosen so as to make the angles between the lines drawn on the card as great as possible. If X and Y were very close together, the angle between the lines drawn through these points would be so small that a very slight error in drawing one of the lines would make a great difference in the position of their point of intersection.

Using the triangular lamina, whose centre of gravity you have just determined, test the truth of the following rules for finding the centre of gravity of a triangle :—

(1) "Join each angle of the triangle to the middle point of the opposite side; the point where these three lines meet is the centre of gravity of the triangle."

(2) "Join any angle of the triangle to the middle point of the opposite side; the centre of gravity of the triangle will divide this line into two parts, one twice as long as the other, the longer part being on the side of the angle."

Experiment 28

Centre of gravity of a quadrilateral.

Draw in your note-book a quadrilateral figure with all four sides of different lengths. Divide this into two triangles by one of the diagonals, and find by either of the rules given above the centre of gravity of each of these triangles. Call these points G_1 and G_2. Then the centre of gravity of the whole figure must lie on the line G_1, G_2.

Then divide the quadrilateral into two other triangles by drawing the other diagonal, and find the centre of gravity G_3 and G_4 of these triangles. Then the centre of gravity of the quadrilateral must lie on the line G_3, G_4. What, then, is the centre of gravity of the quadrilateral?

Experiment 29

To find the centre of gravity of a wire frame.

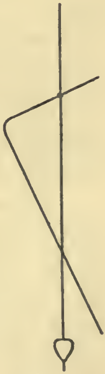

Fig. 76.

Take a piece of copper wire about 20 cm. long, and bend it at right angles at a point so that one arm is twice as long as the other. Suspend it by the short arm from your retort-stand by means of your plumb-line, as in the diagram, having previously made a full-sized drawing of the wire in your note-book.

Hold your note-book behind the wire in such a way that the wire coincides with the drawing, and mark with your pencil the direction of the plumb-line.

Repeat the experiment, hanging the wire from two other points on the short arm.

Then note in your book the position of the centre of gravity. [If the three lines do not accurately meet in a point you must repeat the experiment, hanging the wire from a different point until you obtain a definite point of intersection for at least 3 of the lines thus drawn.]

EXPERIMENT 30

To find the centre of gravity of the wire frame by calculation.

This you can do for yourself if you will make a fresh drawing of the wire, and answer the following questions:—

(1) Where is the centre of gravity of the short arm and of the long arm?

(2) On what line, therefore, must the centre of gravity of the wire lie?

(3) What is the relation between the weights acting at the ends of this line?

(4) What, then, is the relation between the distances of the centre of gravity of the wire from the ends of this line?

(5) Where, therefore, in this line must the resultant of these two weights act?

Then mark this point on your drawing, and measure and record the distance between it and the centre of gravity as found in Experiment 29.

Note.—In making these drawings it will be found most convenient to obtain the second by pricking through points on the first on to a fresh sheet of your note-book. Also prick through the position of the centre of gravity found in Experiment 29.

CHAPTER V

ELASTICITY

In the preceding experiments we have dealt with the effects of forces in keeping bodies at rest, without considering whether the bodies have had their shapes changed in any way by the forces. In fact we have supposed the bodies which we worked with to be *rigid*. It is, however, a matter of common observation that when forces are applied to bodies the size or shape, or both size and shape, of the bodies are changed. In the case of solid bodies we notice that, as a rule, when the force or forces producing the change of shape have been removed, the bodies regain their original shape. Thus, if after pulling out a spiral spring we remove the stretching force, the spring, as a rule, regains its original length. This property of bodies is called **elasticity**, and very little consideration shows that different substances possess this property in very different degrees.

Limit of elasticity.—Again, we may cause so great a change in the shape of a body that, on removing the forces causing the deformation, the body no longer returns to its original shape, but remains somewhat distorted — it has received a "*permanent set*." Thus we may stretch a spiral spring so far that on removing the stretching force the spring does not recover its original length but is per-

manently stretched. Again, if we take a bar of iron and bend it slightly it returns to its original shape, but if we bend it much it remains permanently bent. In all such cases the body is said to have been *strained* beyond its *limit of elasticity.*

Strain is the name given to the change of shape or size of a body produced by forces, and the combination of forces which produces the strain is called a *stress.* Thus the limit of elasticity for any body is that amount of strain which it must receive in order that it should just not return to its original condition after the stress has been removed.

Strain is measured by the proportion which the change of dimensions bears to the original dimension; this will be made plainer by the examples given below. *Stress* is measured by the force exerted *per unit of area*, *i.e.* the number of grammes weight per square centimetre.

Longitudinal strain.—The simplest kind of strain we can deal with is change of length of a wire or rod—elongation or compression—commonly called longitudinal strain, and the *stress* which produces it is called **tension,** or **pressure**, according as the stress produces elongation or compression. In this case the strain is measured by the proportion which the change in length bears to the original length, or

$$\text{Strain} = \frac{\text{change in length}}{\text{original length}}.$$

The *stress* (tension or pressure) is measured by the number of grammes weight per square centimetre of the cross section of the wire or rod.

In Experiment 31 we shall see that within the limit of elasticity the tension is proportional to the strain which it produces. The ratio $\frac{\text{stress}}{\text{strain}}$ for any substance and any kind of strain is called the "Modulus of Elasticity" of the

substance for the given kind of strain. In the case of simple extension the name generally given to this ratio is *Young's Modulus.*

Thus, to find Young's Modulus for any material we must find the increase in length produced by a given stretching force, and divide this by the original length. This gives us the measure of the strain produced. To find the stress, *i.e.* the stretching force per square centimetre, we must divide the stretching force by the area of cross section of the wire measured in square centimetres. Then Young's Modulus $=\frac{\text{stress}}{\text{strain}}$, and is measured in grammes weight per square centimetre.

The same statements are true as regards the shortening of a rod by compression, but experiments on this subject are difficult to make, because when we try to shorten a rod (unless it be short) it bends, and so the kind of strain at once changes.

Bending or flexure.—Suppose we have a beam supported at both ends and loaded in the middle, the strain

Fig. 77.

which is produced is somewhat more complicated than simple extension or compression. For it will be noticed that the fibres composing the beam on the under side are stretched, while those on the upper side are compressed. There must therefore be some fibres near the middle of the beam which are neither compressed nor extended.

The important thing to know about this kind of strain is the *deflection* of the beam for a given load, *i.e.* the distance through which the middle of the beam is lowered by placing a given weight on it. In Experiments 35-38 you will find

the relation between deflection and bending weight, and the effect of changes in the length and thickness of a beam on its deflection for a given bending weight.

The limit of elasticity in this case is reached when on removing the load the beam does not return to its original shape, *i.e.* when it receives a permanent deflection.

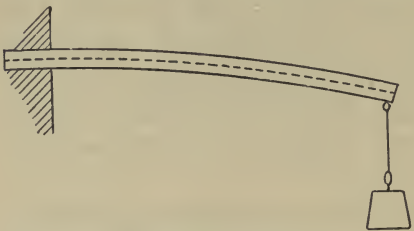

Fig. 73.

A beam may also be bent by fixing it at one end and loading it at the other, as in Fig. 78. This is the case of a tuning fork, in which each prong may be regarded as a beam fixed at one end.

Torsion or twisting.—This again is another kind of strain which is not caused by a force but by a couple (see p. 145). Thus, if we fix a wire or rod firmly at one end A, and apply a couple at the other end, the wire is twisted so that a line which before the twist took place was parallel to the axis of the wire, as AB, is now in the shape of a spiral AC.

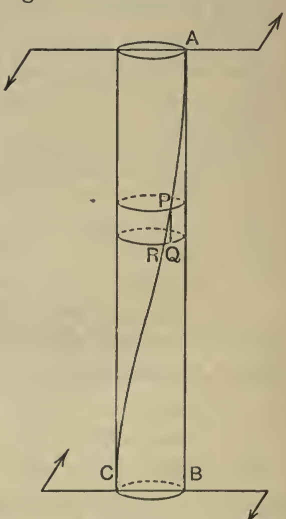

Fig. 79.

If we suppose the wire divided up into a great number of circular discs by being cut through by planes at right angles to the axis of the wire, we see that each disc is turned round a little more than the

one next to it above it. Thus the strain is one in which each little disc slides over the one next to it.

EXPERIMENT 31

To find the relation between the elongation of a stretched wire and the force producing it when the wire is stretched within its limit of elasticity. (*Hooke's Law*).

Take two pieces of wire (brass or copper or steel), about 1 mm. diameter or less, and fix them to a support, so that when weights are attached to their free ends the wires hang side by side a few centimetres apart. The wires should be as long as can be conveniently suspended in this way from some firm support, and it is well to fix them in steel clamps like small vices screwed into a beam in the ceiling. To one wire hang a weight heavy enough to keep it tightly stretched, and to the other attach a scale pan sufficiently large and strong to carry weights up to 20 or 30 kgm. The former wire should be shorter than the latter, so that the two wires may be able to hang close together without the shorter wire being touched by the scale pan.

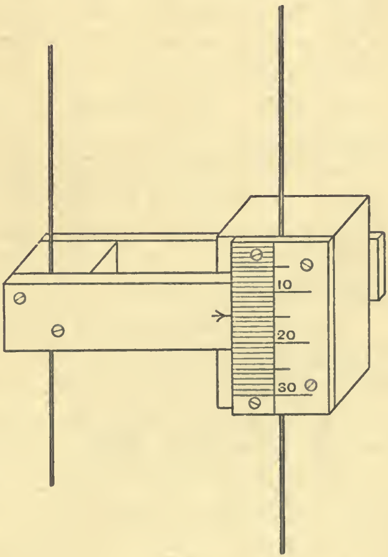

Fig. 80.

Clamp on to the shorter wire, close to the weight, a short piece of a millimetre scale, and fix to the longer wire a wire-pointer long enough to reach across to this scale. A convenient arrangement, and one which can be very easily made, is shown in Fig. 80. Here, instead of a wire-pointer, we have a flat piece of wood with its edge coming up to the edge of the scale and having an arrow-head marked on it, whose position on the scale can be estimated with considerable accuracy to one-tenth of a millimetre. A second piece of wood is shown parallel to the index piece, the object of which is to prevent the pointer from swinging away from the scale. Place in the scale pan a weight sufficiently heavy to stretch the longer wire quite straight, and read the position of the pointer on the scale. Measure as accurately as you can the length of the wire from its point of support to the arrow-head. Also measure, by means of a gauge, the diameter of the wire, or ask your teacher to do it for you. Record these in your note-book. Then place 2 kgm. more in the scale pan, and read the position of the pointer. Do this several times, adding 2 kgm. each time.

Then remove all the weights carefully and notice whether the wire contracts to its original length.

Calculate the elongation produced by each of these weights and write down thus :—

Stretching Weight.	Position of Pointer.	Elongation.	$\dfrac{\text{Elongation}}{\text{Stretching Weight}}$.
2 kgm. 4 ,, 6 ,, 8 ,, etc.			

What then is the relation between the force stretching a wire and the elongation produced by it?

Plot on a sheet of squared paper the results obtained, making abscissæ represent stretching force and ordinates the elongation. Draw freehand a smooth curve, so as to include as many of the points as possible. This curve will be found to be a straight line, showing that stretching force and elongation are proportional to one another.

This relation between the force producing elongation of a wire and the elongation produced is generally known as "Hooke's Law," from its discoverer.

Can you suggest a reason for fixing the scale to the short wire instead of having only a single wire and fixing the scale to the wall or table? What sources of error are avoided by doing so?

* Experiment 32

Calculate Young's Modulus for the material of which the wire used in last experiment is made.

Find from the results of last experiment the average value of the elongation produced by 2 kgm. weight added to the stretching force. Then calculate the strain produced by the 2 kgm. weight as shown on p. 155.

Knowing the diameter of the wire, find its radius and calculate the area of its cross section. In doing this be careful to see that your radius is expressed in centimetres, so that your area may be in square centimetres. Knowing the area of cross section, find the force which would have been required to produce the same elongation if the area of cross section had been 1 sq. cm., *i.e.* find the force exerted *per square centimetre*, this is the *stress*.

Then divide stress by strain correct to three significant figures. The result will be Young's Modulus expressed in kilogrammes weight per square centimetre.

Experiment 33

To find whether stretched indiarubber obeys Hooke's Law.

Fix a piece of indiarubber cord about 20 cm. long in the clamp of your retort-stand, and attach to the free end a scale pan by means of a string about 20 cm. long. Pass a pin through the indiarubber at its free end and at right angles to its length, and fix to another clamp on your retort-stand a half-metre measure vertically with its zero end at the fixed end of the indiarubber, so that by means of the pin we can at once measure the elongation produced in the cord by adding weights to the scale pan.

Place weights in the scale pan, increasing them each time by 100 gm., and note the position of the pin on the scale. Write down your results in a table thus :—

Weight.	Position of Pin.	Elongation.
100 gmwt.		
200 ,,		
300 ,,		
etc.		

On a sheet of squared paper plot your results as in last experiment, and state whether Hooke's Law is true in this case, and if not in what way it is deviated from.

Find the limit of elasticity in this case.

Experiment 34

To find the relation between the elongation of a spiral spring and the force causing it.

To do this all that is necessary is to examine your dynamometer. Since it is already graduated in grammes weight,

you need only measure the distances from "0" to "100," "200," etc., on the scale.

Plot on a sheet of squared paper your results, making abscissæ represent stretching force and ordinates the elongation. What is the shape of the curve which most nearly contains all the points on your diagram, and what, therefore, is the relation between stretching weight and elongation?

Experiment 35

To prove that the deflection produced at the middle of a beam supported at both ends is proportional to the bending weight so long as the beam is not bent beyond its limit of elasticity.

Take a beam (a metre measure answers very well) and

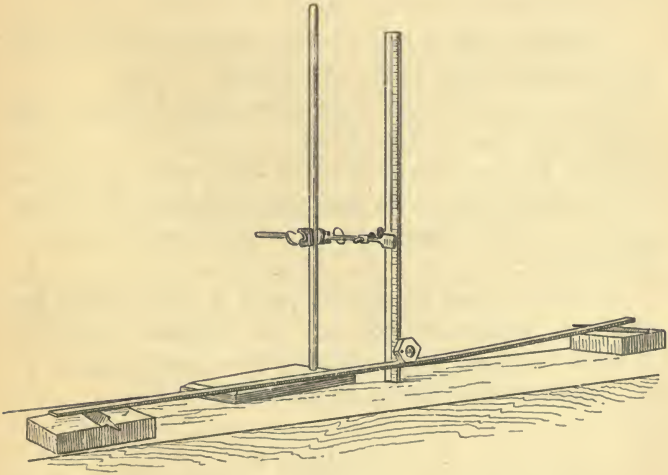

Fig. 81.

place it with its two ends resting on triangular files, as in Fig. 81.

Fix in your retort-stand a half-metre measure vertically, with its edge in contact with the lower side of the beam at its middle point, and its zero end touching the table, so that you may easily and accurately measure the height above the table of the lower side of the beam. Note this height when no load is on the beam, then note the heights when loads of 50, 100, 150, 200, 250, etc., gm. are placed in the middle of the beam, and so calculate the amount of deflection produced by each load, arranging your results in tabular form thus :—

Load.	Height above Table.	Deflection.	$\frac{\text{Load}}{\text{Deflection}}$.

Divide the load in each case by the deflection produced, and place the results in the last column.

State whether the statement made above is true for all the observations you have made.

After the last observation has been made remove the load, and see whether the beam has returned to its original position. Has it then been stretched beyond its limit of elasticity ?

Draw on a sheet of squared paper a curve, having for abscissæ bending weights and for ordinates deflection. What is the shape of the curve that most nearly contains all the points obtained from your measurements ?

Experiment 36

To find the relation between the thickness of a beam and the flexure produced by a given bending weight.

For this you require a number of laths of the same

material, length, and breadth, but of thicknesses varying from about 1 mm. to 1 cm. Arrange each in turn on two triangular files, as in last experiment, and find the load required to produce a given deflection, say 3 mm. Care must be taken that the distance between the files must be the same in each case, and that the deflection with and without load should be noted with great care in order that the deflection in each case may be exactly the same. The thickness of each lath should be measured in several places and the mean taken.

Arrange your results as follows :—

Thickness of Beam.	Bending Weight to Produce Given Deflection.

On a piece of squared paper plot your results, making abscissæ to represent thickness and ordinates bending weights. The shape of this curve shows that the bending weights increase much more rapidly than the thicknesses, and so the relation between them cannot be one of simple proportionality. Then find the square of each thickness correct to three significant figures, and draw up a table as follows :—

Square of Thickness.	Bending Weight.

Plot these results against each other as before on the same sheet of paper, taking abscissæ to represent *square of thickness* and ordinates bending weight as before. (You

will probably require to take a different scale for abscissæ from what you used before.) In this case, again, you will find that the curve is concave upward, showing that the bending weights increase more rapidly than even the squares of the thickness.

Next work out to three significant figures the cubes of the thicknesses. Draw up a table, and plot a curve as before, having abscissæ representing cube of thickness and ordinates bending weight. State whether the curve you have drawn is concave upwards, straight, or concave downwards.

State thus, as a result of your work, what is the relation between the thickness of a lath and the bending weight required to produce a given flexure.

Thence find what is the relation between the thickness of a lath and the flexure produced by a given bending weight, knowing from last experiment that for the same lath the flexure is proportional to the bending weight.

Experiment 37

Second method of finding the law of variation of bending weight with thickness.

Having drawn on a sheet of squared paper the curve showing the relation between bending weight and thickness, write down the cubes of the numbers 1, 2, 3, 4, 5, 6, etc., viz. 1, 8, 27, 64, 125, etc.

Plot on the same sheet of squared paper the relation between the cubes and the numbers, the cubes being taken as ordinates, and choose the scale of ordinates in such a way that the ordinate for any one abscissa, say "5," is the same as the corresponding ordinate of the curve already drawn. Thus the curve of cubes and the curve of bending weights must coincide at one point. If they coincide at all points, or if they keep close together, then the relation

between bending weight and thickness must be the same as that between the cube of a number and the number. But if one curve gets further and further away from the other the relation cannot be the same.

EXPERIMENT 38

To find the relation between the length of a beam and the deflection produced by a given bending weight, other things being the same.

Take a series of laths of exactly the same material, thickness, and width, but of different lengths, ranging from about 30 cm. to 100 cm. Place them in turn upon two triangular files, as in previous experiment, carefully noting the distance between the files in each case. Measure and record the bending weight required to produce the same deflection (2 or 3 mm.) in each case, as in last experiment.

Plot on a sheet of squared paper, as before, the observations you have made, taking abscissæ to represent lengths and ordinates to represent bending weights. As in previous experiments, draw freehand the smooth curve which most nearly contains all these points. In this case it will be found that the curve slopes downwards from left to right, since the longer the beam the less weight is required to produce a given deflection.

Having drawn the smooth curve, write down the corrected values of the bending weight for each length obtained from it. For example, if you found that for a length of 70 cm. the bending weight was 67 gm., but that the smooth curve has an ordinate representing 65 gm. for an abscissæ of 70, you would write down the latter value in your table, since it is more likely to be correct than the former.

Then write down in a third column the cube of the

length of the lath, *i.e.* the distance between the files, and multiply this by the bending weight, writing your result in the fourth column. We thus get a table like the following :—

Length.	Bending Weight.	(Length).^{3}	Bending Weight × (Length).^{3}
cm.	gmwt.		
100	21	1,000,000	21,000,000
90	30	729,000	21,870,000
80	40	512,000	20,480,000

If the numbers in last column were all the same, what would be the relation between bending weight and cube of length? What conclusion, then, do you draw as to the results of your experiment, *i.e.* are the numbers in the last column sufficiently nearly equal to one another to justify you in saying what is the relation between length and *bending weight?* (See p. xvii, "Inverse Proportion.")

What, then, is the relation between length of beam and *deflection* produced by given bending weight?

THE END

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